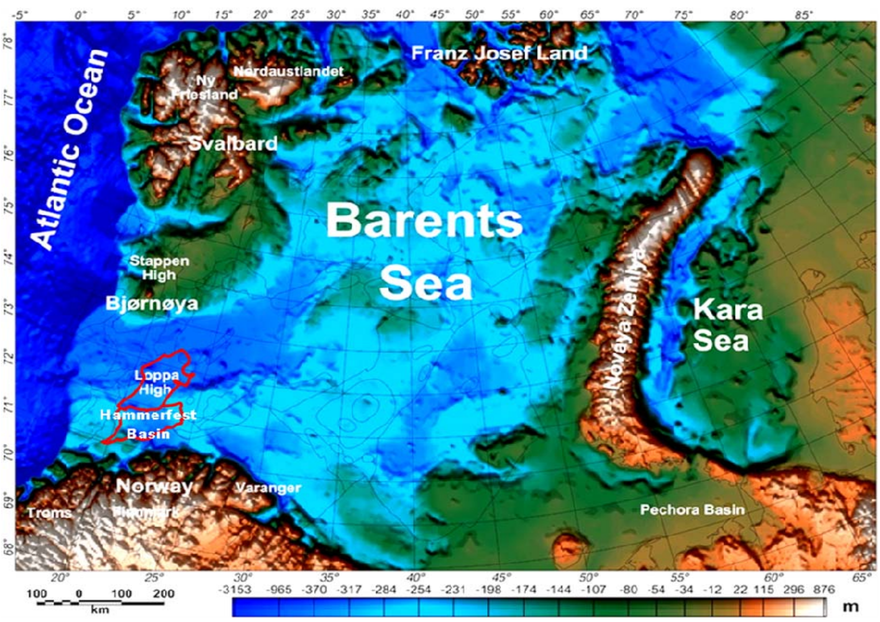
Master Thesis in Geosciences

Late Jurassic - Early Cretaceous subsidence and deposition in the NE Hammerfest Basin linked to uplift and erosion of the Loppa High, SW Barents Sea.

BELALAHY Olivier



UNIVERSITY OF OSLO
FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Late Jurassic – Early Cretaceous subsidence and deposition in the NE Hammerfest Basin linked to uplift and erosion of the Loppa High, SW Barents Sea

BELALAHY Olivier

Master Thesis in Geosciences

Discipline: Petroleum Geology and Geophysics (PEGG)

Department of Geosciences

Faculty of Mathematics and Natural Sciences

UNIVERSITY OF OSLO

June 2009

Tutor(s): Prof. Jan Inge Faleide; Prof. Johan Petter Nystuen and Dr. Michel Heeremans

Preface

The present M.sc. thesis is the result of two years study in Petroleum Geology and Geophysics started in 2007 at the Department of Geosciences, University of Oslo. This work is a part of the PETROBAR project and based on seismic interpretation.

Acknowledgements

I wish to express all my gratitude to Prof. Jan Inge Faleide, my principal supervisor and Prof. Johan Petter Nystuen, co-supervisor, for their supervision, kind help and great patience during this work. The encouragement and support I received from both are invaluable for the completion of this thesis.

I also owe Special thanks to Dr Michel Heeremans, co-supervisor, who helped in data handling and software manipulation.

And my very special thanks to my wife Hanta and my sons Princy, Andy and Lucas for their great love, unlimited patience and support during two years.

June 2009

BELALAHY Olivier

Contents

1. Introduction

The Barents Sea is a part of the world's largest shelf region. In spite of an exploration history over the last 30 years, only few discoveries of commercial interest have been made.

The Hammerfest Basin is one of the areas where oil exploration started in the western part of the Barents Sea. The major gas discovery in the Snøhvit field and the more recent oil discovery in the Goliat field, both located in the Hammerfest Basin, encouraged the research for commercial oil accumulation, making the exploration drilling more widespread the last years.

Uplift movements, followed by erosion are amongst the main reason of the lack of success in oil discovery. Such processes can dramatically affect the petroleum system, in terms of destruction of oil accumulation, and need to be carefully analysed. Such events occurred between the Loppa High and the Hammerfest Basin several times and a good understanding is necessary to guide in the research for source rocks, reservoir rocks and the migration path connecting them.

This thesis work aims to study the differential vertical movement between the NE Hammerfest Basin and Loppa High during Late Jurassic - Early Cretaceous times. This has been be accomplished mainly by interpretation of 2D c and 3D seismic data, after seismic to well ties and stratigraphic calibration. Chronostratigraphic charts have been produced from the interpreted profiles on three key lines, chosen along the strike of the Hammerfest Basin. As a result, a synthesis of the Late Jurassic – Early Cretaceous evolution of the Hammerfest Basin has been performed and put into a regional context.

The present thesis is a part of PETROBAR ("Petroleum-related regional studies of the Barents Sea region") which is a large interdisciplinary regional research project focussing on increased understanding of fundamental large-scale processes behind sedimentary basin formation and evolution in the Barents Sea region and their impact on the petroleum systems, in order to reduce exploration risks (Faleide 2008).

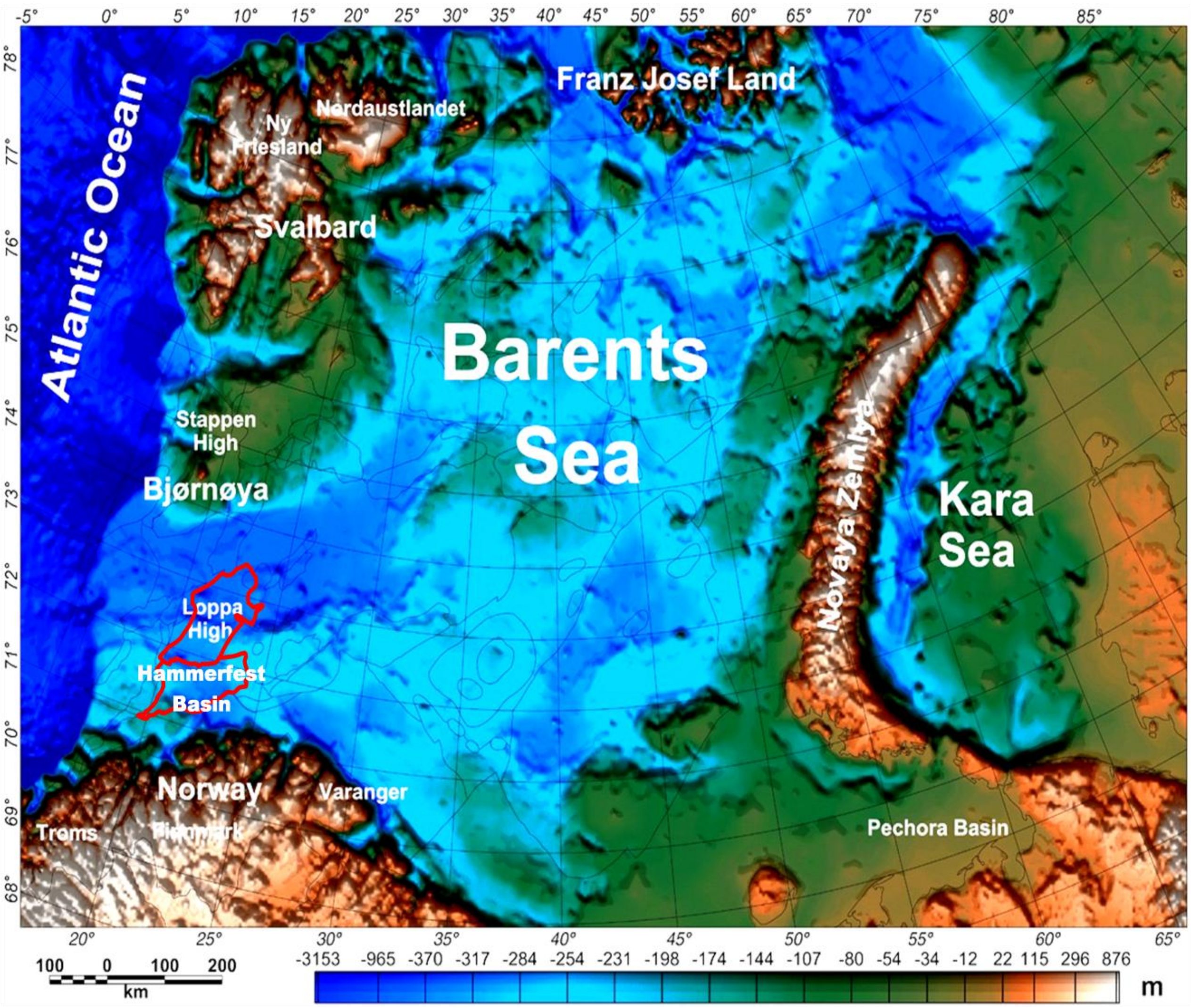


Figure 1.1. Regional setting and location of the study area (Modified from Barrère et al., 2008).

2. Geological setting

2.1. Regional setting

The Barents Sea covers the northwestern corner of the Eurasian continental shelf. It is bounded by young passive margins to the west and north that developed in response to Cenozoic opening of the Norwegian-Greenland Sea and the Eurasia Basin, respectively. The western Barents Sea is underlain by large thickness of Upper Paleozoic to Cenozoic rocks constituting three distinct regions (Faleide et al., 1993):

- The Svalbard Platform covered by a relatively flat lying succession of Upper Paleozoic and Mesozoic, mainly Triassic, sediments;
- A basin province between the Svalbard Platform and the Norwegian coast characterized by a number of subbasins and highs with an increasingly accentuated structural relief westwards – Jurassic-Cretaceous, and in the west Paleocene-Eocene, sediments are preserved in the basin;
- The western continental margin consists of three main segments (a) a southern sheared margin along the Senja Fracture Zone; (b) a central rifted complex south-west of Bjørnøya associated with volcanism and (c) a northern, initially sheared and later rifted margin along the Hornsund Fault Zone. The continent-ocean transition occurs over a narrow zone along the line of Early Tertiary breakup and the margin is covered by a thick Upper Cenozoic sedimentary wedge.

The post-Caledonian geological history of the western Barents Sea is dominated by three major rift phases: Late Devonian-Carboniferous; Middle Jurassic-Early Cretaceous and Early Tertiary, each comprising several tectonic pulses. During Late Palaeozoic times most of the Barents Sea was affected by crustal extension. The later extension is characterized by general westward migration of the rifting, formation of well-defined rifts and pull-apart basins in the southwest, and the development of a belt of strike-slip faults in the north. Apart from epeirogenic movements which produced the present day elevation differences, the Svalbard Platform and the eastern part of the regional basin have been largely stable since Late Palaeozoic times.

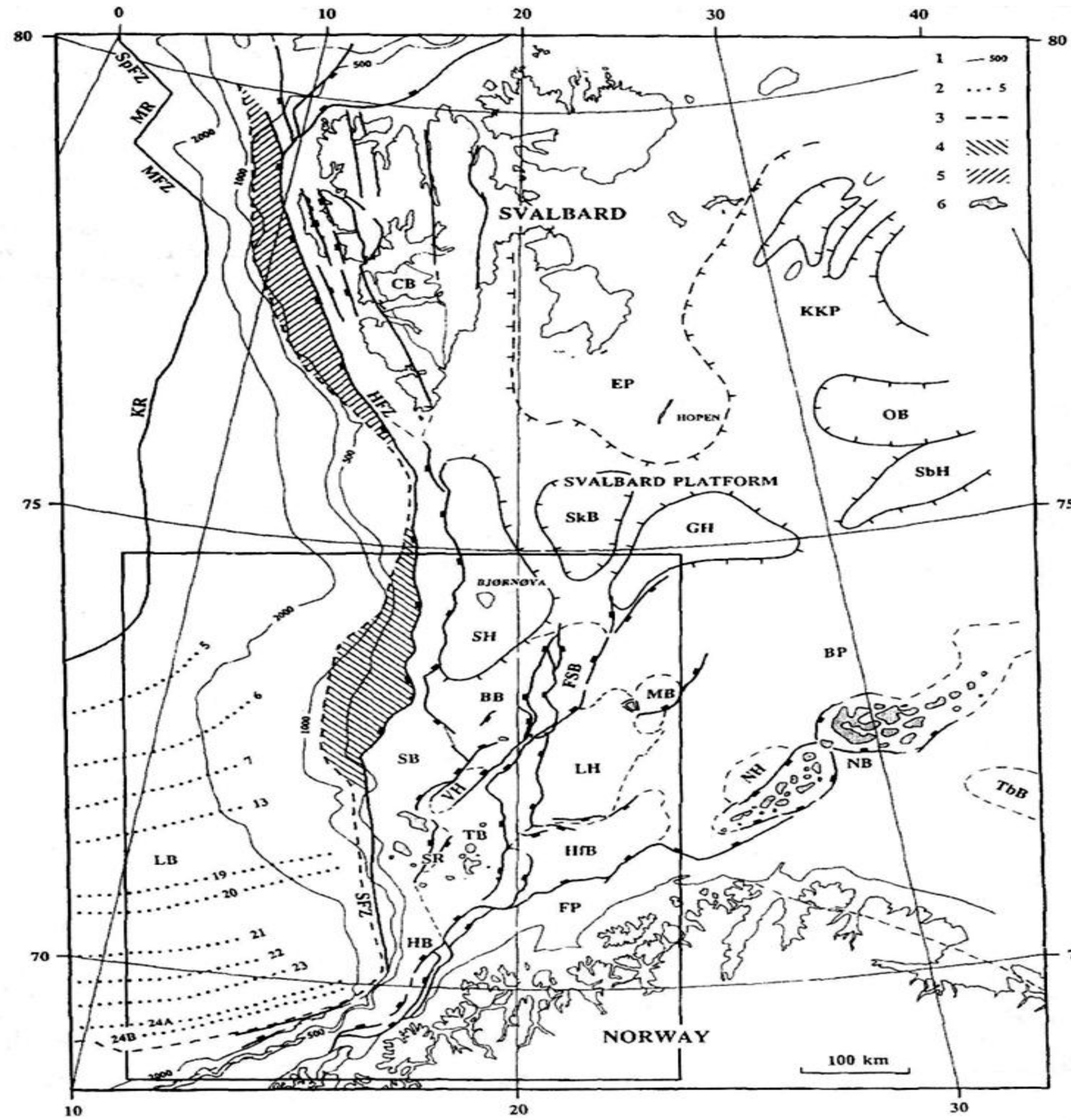


Figure 2.1. Regional structural map of the western Barents Sea. Structural elements on the Svalbard Platform from Gabrielsen et *a/.(1990). 1 =* bathymetry (m); 2 = magnetic lineations; 3 = limit of identified oceanic crust in the seismic sections; 4 = Vestbakken volcanic province; 5 = Tertiary stretched continental crust; 6 = salt. BB = Bjørnøya Basin; BP = Bjarmeland Platform; CB = Tertiary Central Basin (Spitsbergen); EP = Edgeøya Platform; FBS = Fingerdjupet Subbasin; GH = Gardarbanken High; HB = Harstad Basin; HfB = Hammerfest Basin; HFi = Hornsund Fault Zone; KKP = Kong Karl Platform; KR = Knipovich Ridge; LH = Loppa High; MFZ = Molloy Fracture Zone; MR = Molloy Ridge; NB = Nordkapp Basin; OB = Olga Basin; SB = Sørvestsnaget Basin; SbH = Sentralbanken High; SF2 = Senja Fracture Zone; SH = Stappen High; SkB = Serkapp Basin; SpFZ = Spitsbergen Fracture Zone; SR = Senja Ridge; TB = Tromsø Basin; FP = Finnmark Platform; VH = Veslemøy High. (Faleide et al., 1993).

The Barents Sea sedimentary cover in places exceeds 15 km and the south-western part of the Barents Sea contains some of the deepest sedimentary basins world-wide (Faleide et al., 1993).

2.2. South-western Barents Sea

2.2.1. Location and structure

On the basis of sedimentary fill, tectonic style and structure, three main geological provinces separated by major fault zones can be recognized in the south-western part of the Barents Sea (Faleide et al., 1993):

- The oceanic Lofoten Basin which formed during the Cenozoic opening of Norwegian-Greenland Sea and the Vestbakken Volcanic Province;

- The south-western Barents Sea basin province of deep Cretaceous and Early Tertiary basins (Harstad, Tromsø, Bjørnøya and Sørvestsnaget basins) separated by intrabasinal highs (Senja Ridge, Veslemøy High and Stappen High); and

- Mesozoic basins and Highs further east between 20 and 25°E which have not experienced the pronounced Cretaceous-Tertiary subsidence (Finnmark Platform, Hammerfest Basin, Loppa High and Fingerdjupet subbasin).

These provinces are separated by the continental boundary faults along the Senja Fracture Zone and the eastern boundary of the Vestbakken Volcanic Province, and the main Jurassic-Cretaceous faults bounding the deep Cretaceous basins. These are the Troms-Finnmark Fault Complex south of 71°N, the Ringvassøy-Loppa Fault Complex, Bjørnøyrenna Fault Complex and Leirdjupet Fault Complex (Gabrielsen et al., 1990).

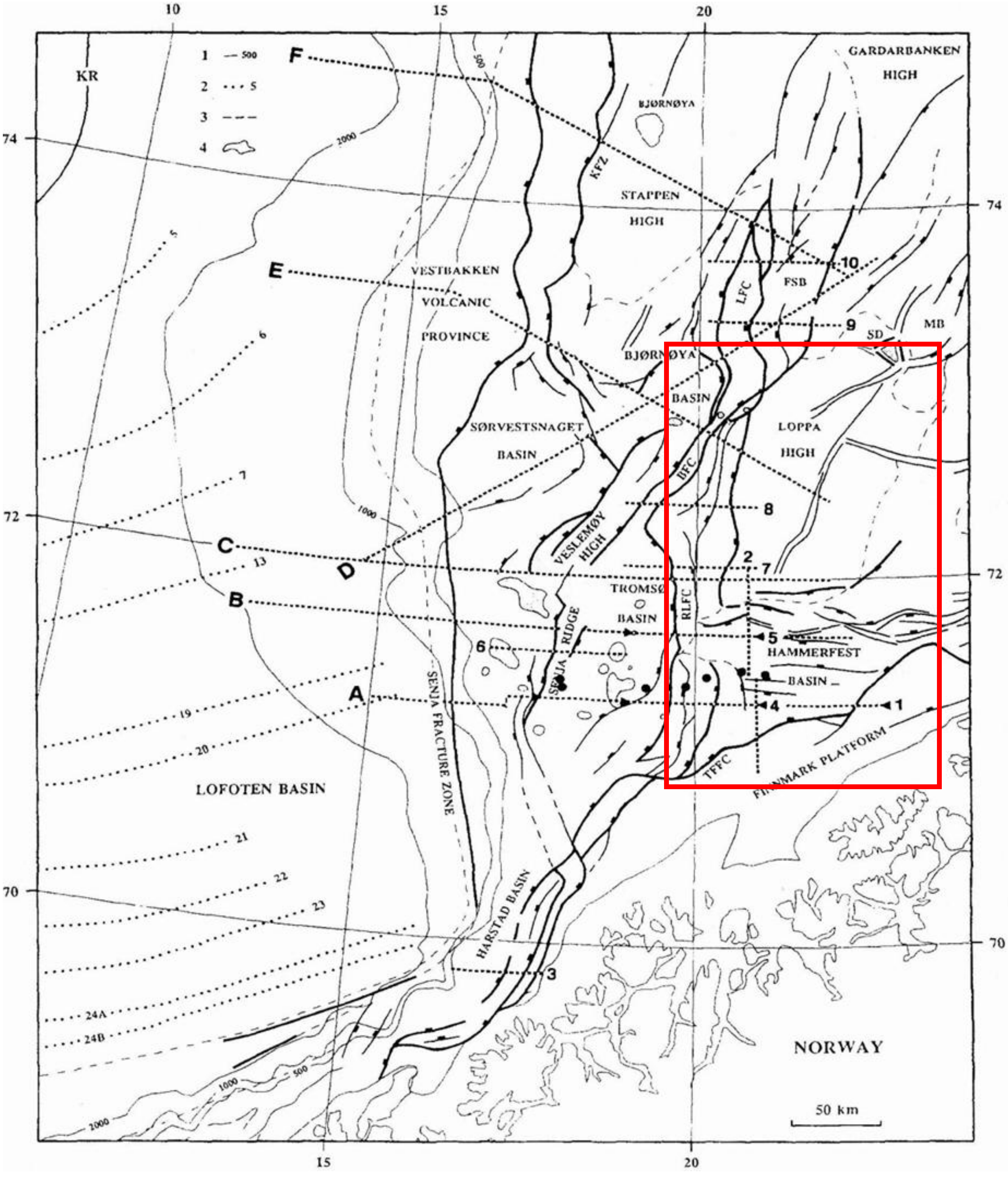


Figure 2.2. Regional structure map showing main structural features and the location of the study area. AFC = Asterias Fault Complex; BFC = Bjørnøyrenna Fault Complex; FSB = Fingerdjupet Subbasin; KFZ = Knølegga Fault Zone; KR = Knipovich Ridge; LFC = Leirdjupet Fault Complex; MB = Maud Basin; RLFC = Ringvass0y-Loppa Fault Complex; SD = Svalis Dome; TFFC = Troms-Finnmark Fault Complex – (Faleide et al., 1993).

Hammerfest Basin

The Hammerfest Basin, which was identified by Rønnevik et al. (1975) is relatively shallow and has an ENE-WSW striking axis. It is situated between 70°50′N, 20°E, 71°15′N, 20°E, 72°15′N, 23°15′E and 71°40′N, 24°10′E. The basin is separated from the Finnmark Platform to the south by the Troms-Finnmark Fault Complex and from the Loppa High to the north by the Asterias Fault Complex (Figures 2.2 and 2.3). Its western limitation towards the Tromsø Basin is defined by the southern segment of the Ringvassøy-Loppa Fault Complex, whereas its eastern border at the reference level has the nature of a flexure against the Bjarmeland Platform (Gabrielsen et al., 1990). The Hammerfest Basin may be subdivided into a western and an eastern subbasin (Ziegler et al., 1986), separated by the extension of the Trollfjord-Komagelv fault trend (Gabrielsen & Færseth., 1989).

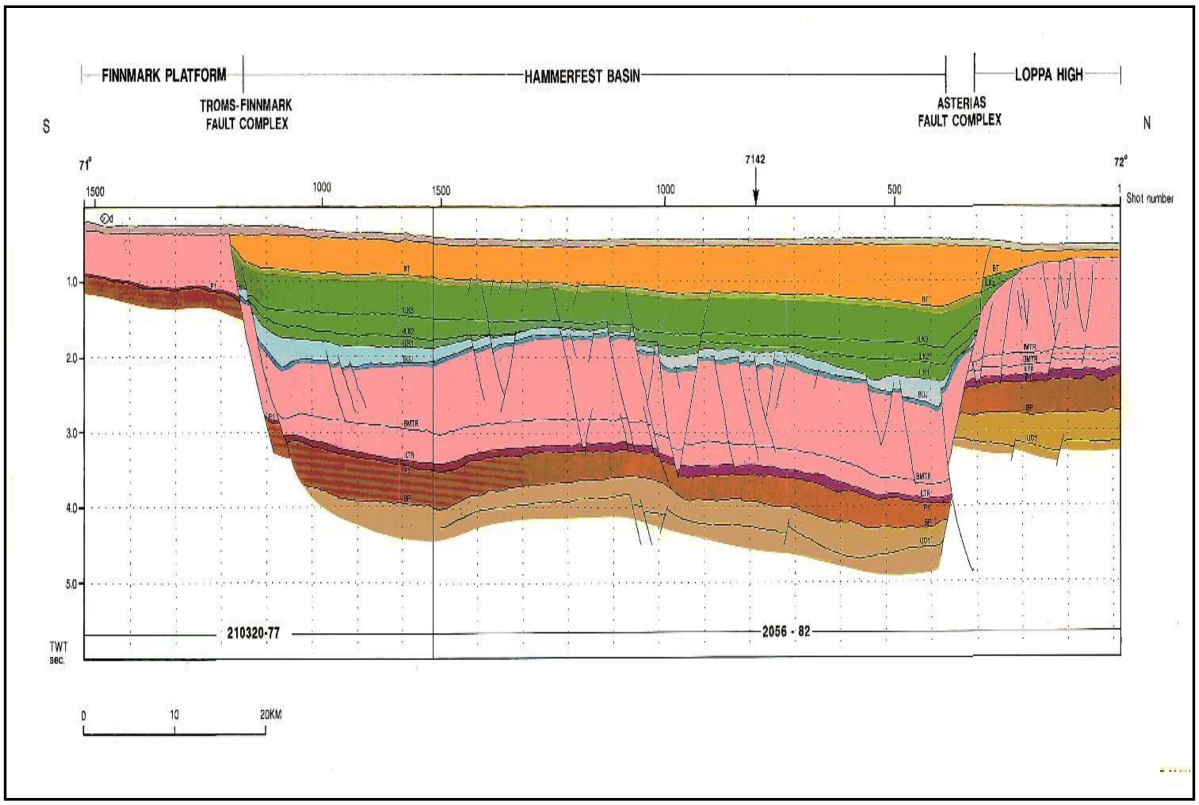


Figure 2.3. Composite profile lines 210320 and 2056 showing the main structural features of the Hammerfest Basin (Gabrielsen et al., 1990).

The western part of the Hammerfest Basin dips generally westwards towards the Tromsø Basin. It is characterized by a gentle central dome paralleling the basin axis, and an internal fault system composed of E-W, ENE-WSW and WNW-ESE trending faults informally termed the Hammerfest Basin fault system by Gabrielsen (1984). The Hammerfest Basin includes deep, high-angle faults along the basin margins and listric normal faults detached above the Permian sequence, situated more centrally in the basin (Figure 2.2 - Berglund et al., 1986). Structuring of the Hammerfest Basin has been dominated by extension, although it has been suggested that the deformational style indicates reactivation by strike-slip in the Late Jurassic to Early Cretaceous (Berglund et al., 1986, Sund et al., 1986, Gabrielsen and Færseth 1989, Gabrielsen et al., 1990). The eastern part of the basin is generally less affected by faulting, and has the characteristics of a sag basin (Gabrielsen et al., 1990).The depth to basement in the Hammerfest Basin has been calculated to 6–7 km (Roufosse, 1987).

The Hammerfest Basin has been interpreted as a failed rift in a triple junction (Talleras., 1979) and as a remnant of an older rift system overprinted by younger one (Hanisch., 1984 a, b). Rønnevik et al. (1982) and Rønnevik and Jacobsen (1984) emphasized the influence of strike-slip faulting in the development of the fault complexes encompassing the basin. This has been followed up by suggestions that the history of the Hammerfest Basin may be linked with transfer faulting associated with major gravity-induced movements (Ziegler et al., 1986), and rotation of regional fault blocks around a vertical axis (Gabrielsen and Færseth 1988, Gabrielsen et al., 1990).

Outlines of architecture of the individual major fault complexes around and within the Hammerfest Basin are shown in Figure 2.4, according to Berglund et al., (1986). Five different types have been distinguished:

- *Type 1* is represented by the Troms-Finnmark Fault Complex (TFFC), and is characterized by listric fan complexes dominated by one or two major listric faults, often associated with roll-over anticlines and antithetic faults.
- *Type 2* is typical for the Ringvassøy-Loppa Fault Complex (RLFC) which is characterized by a large number of normal faults, reactivated several times.
- *Type 3* represents the earlier called Southern Loppa High Fault Complex or the Asterias Fault Complex (AFC). This fault zone is characterized by two large southerly-dipping normal faults, associated with a very complex pattern of smaller southerly- and northerly dipping faults often dissecting each other. It is suggested that at the end of the Jurassic times this fault zone had a compressional strike-slip component, when updoming

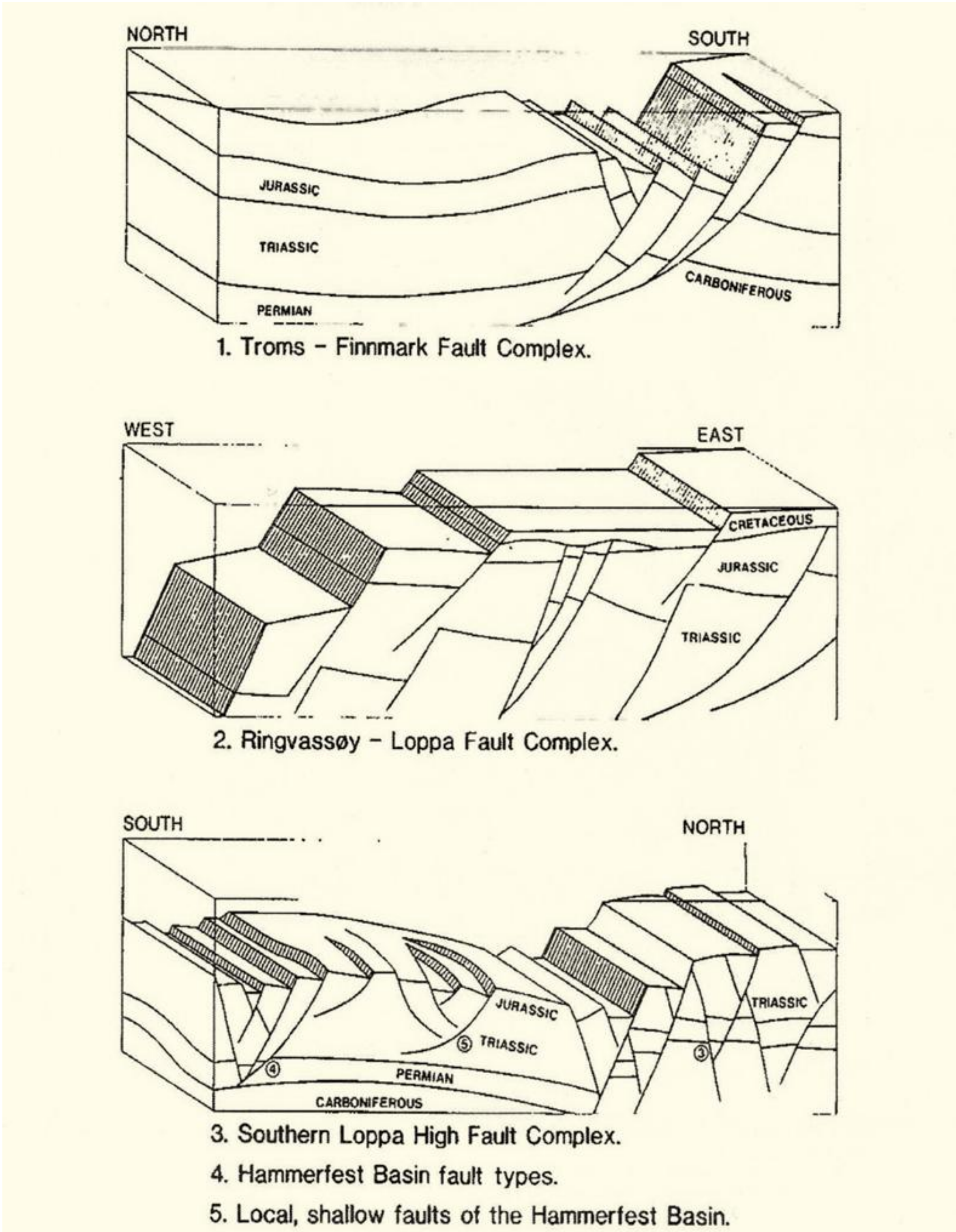


Figure 2.4. Fault-types in the Hammerfest Basin (Berglund et al., 1986).

and "flower structures" were formed. This structure collapsed into normal faults at the beginning of Cretaceous time under a tensional regime. Towards the east the fault complex passes into a large flexure separating the Loppa High from the Hammerfest Basin.

- *Type 4* is the E-W-oriented normal faults of the Hammerfest Basin. Initially these faults are believed to have formed under a transtensional strike-slip regime simultaneously with an updoming along the AFC at the end of Jurassic times and were later reactivated in Early Cretaceous times under a tensional stress.
- *Type 5* is also located in the Hammerfest Basin and is characterized by shallow faults which do not penetrate the lower Triassic succession. The architecture of these fault-planes may resemble that of growth-faults; however, no other indications of growth-faulting are present.

The main fault trend of the Hammerfest Basin and the western Barents Shelf represent basement grains which have been repeatedly reactivated through time. The structures outlined in Figure 2.2 result from the complex interaction of a number of tectonic episodes. Additional complexities result from halokinetic movements of Palaeozoic salt intervals.

Loppa High

The Loppa High, which incorporates the Polhem Platform, is situated north of the Hammerfest Basin and southeast of the Bjørnoya Basin as showed in Figure 2.2 (Gabrielsen et al., 1990). The high, which is diamond shaped in outline, is situated between 71°50′N, 20°E, 71°55′N, 22°40′E and 72°55′N, 24°10′E and 73°20′N, 23°E. It consists of an eastern platform and a crestal western and northwestern margin. It is bounded on the south by the Asterias Fault Complex and on the east and southeast by a monocline towards the Hammerfest Basin and the Bjarmeland Platform. To the west, the Loppa High is bounded by the Ringvassøy-Loppa and Bjørnøyrenna Fault Complexes. A major salt structure, the Svalis Dome, and its associated rim syncline, the Maud Basin, mark the northeastern limit of the high. The Loppa High is associated with positive gravity and magnetic anomalies caused by a relatively shallow metamorphic basement of Caledonian age underlying its western part (Gabrielsen et al., 1990).

The Loppa High is a result of Late Jurassic to Early Cretaceous and Late Cretaceous - Tertiary tectonism. From Ladinian to Callovian times, the high was part of a regional cratonic platform including the Hammerfest Basin and Bjarmeland Platform (Gabrielsen et al., 1990). During most of the Cretaceous, Loppa High was an island with deep canyons cutting into the Triassic sequence. The high was covered by Paleogene shales, most of which were eroded during the Late Tertiary uplift.

Asterias Fault Complex

The Asterias Fault Complex is the main boundary fault which separates the Hammerfest Basin from the Loppa High and has an East-West trend. The fault complex can be divided in two segments along its strike: in the western part it is a normal fault whereas it dies out into a Flexure as it begins to trend in a North-Northeast direction. To the west of 21° 15E, it shows evidence of half-flower structures, local doming and inversion (Gabrielsen., 1990). Genetically, The Asterias Fault complex is believed to be due to deep extensional faulting.

2.2.2. Stratigraphy

Worsley et al. (1989) proposed a Mesozoic and Cenozoic lithostratigraphy offshore northern Norway which comprises seven groups, mainly based on well data from the Hammerfest Basin (Figure 2.5). A stratigraphic summary is given by Faleide et al. (1993) using the proposed lithostratigraphic framework.

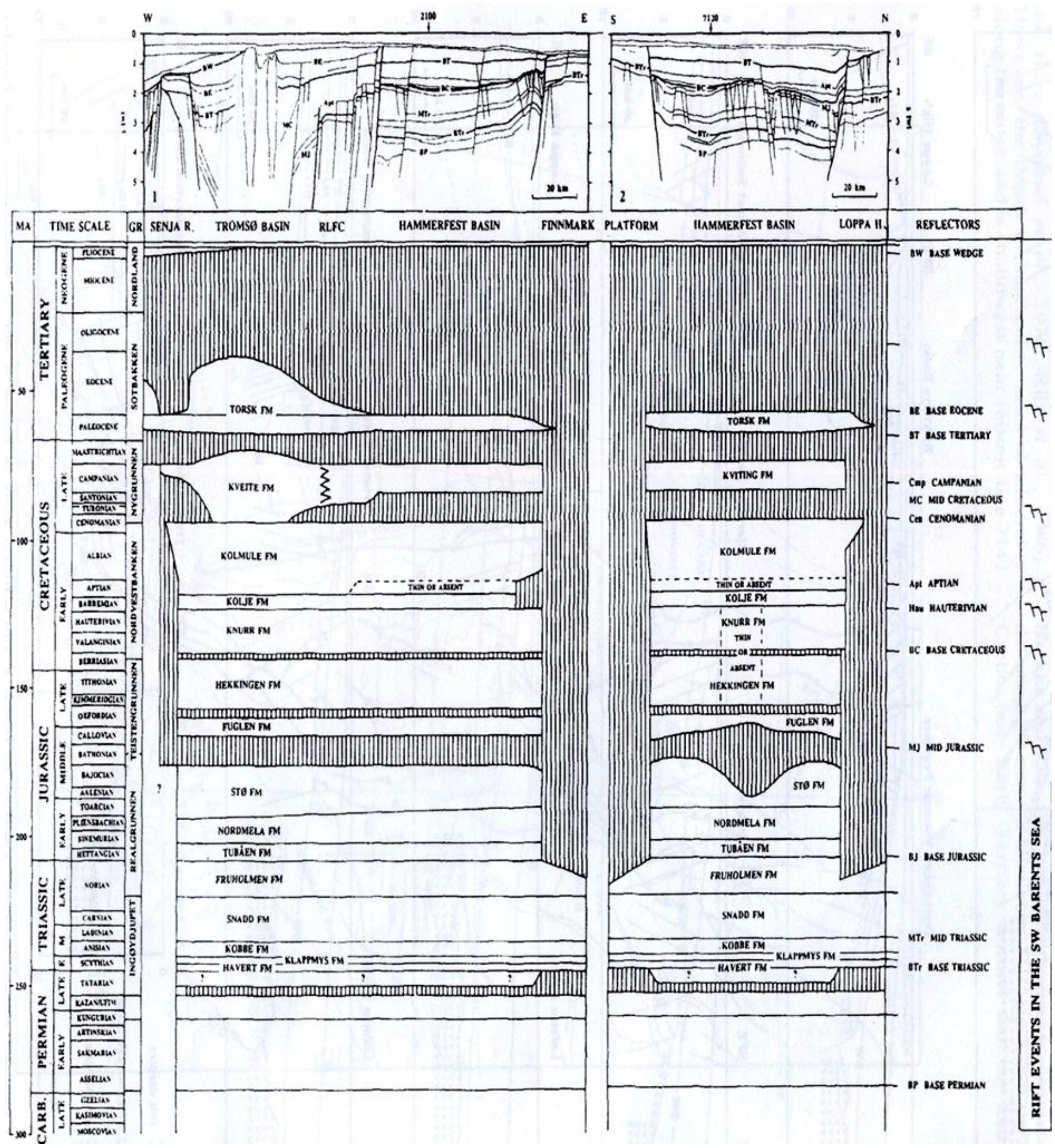


Figure 2.5. Lithostratigraphy based on Worsley et al. (1989).

According to the time interval defined by the objectives of this study, focus is put on the stratigraphical units ranging from the Upper Triassic up to the Quaternary.

Upper Triassic – Middle Jurassic

Ingøydjupet Group is thick throughout the Barents Sea and comprises four formations ranging in age from early Scythian to early Norian. All contain shales at the base, overlain by coarsening-upward sequence indicating transgressive-regressive depositional cycles (Mørk et al. 1989). The base of the overlying Realgrunnen Group, of early Norian to Bajocian age, is defined by shales representing an important transgressive episode which produced a sequence boundary traceable from the southwestern Barents Sea to Sverdrup Basin (Mørk et al., 1989). Condensed sequences and a locally erosive top caused by Kimmerian uplift give rise to a seismic marker, which can be followed over large areas of southern Barents Sea. The group is present throughout the Hammerfest Basin, probably thickening into the Tromsø Basin. These sediments are believed to have covered also the Loppa High and Finnmark Platform, but were partly eroded during the later tectonic activity (Faleide et al., 1993). Sandstones dominate, especially in the middle and upper parts, whereas shales are most common in the lower part (Worsley et al., 1988). In detail, the series begin with coastal plain and tidal flat shale/sand series in the Fruholmen and Tubåen Formations, and passes to near-shore and inner shelf sands paralic environment in the Nordmela formation and open shelf to the Stø Formation. The middle Jurassic sandstones of the Realgrunnen Group form the most potential reservoir of the whole Barents Sea's lithostratigraphic column.

The Middle - Upper Jurassic Teistengrunnen Group is bounded by major unconformities which range from late Callovian to late Berriasian in age although the late Bathonian/early Callovian interval may be present locally. The basal unconformity marks the onset of rifting in the southwestern Barents Sea, whereas unconformities within the group reflect interplay between continued late Jurassic faulting and sea level changes. The group shows great variations in thickness, being thinnest on the structural highs in the central Hammerfest Basin and thickening towards the basin boundary faults to the north, south and west. The shales and claystones contain thin interbedded marly dolomitic limestones and rare siltstones or sandstones towards the basin flanks reflecting relatively deep and quiet marine environments (Worsley et al., 1988).

The Lower Cretaceous Nordvestbakken Group comprises three formations from Valanginian to Cenomanian. Thickness variations in the Hammerfest Basin are related to basin-parallel structures with the thinnest sequences over the central dome. The group thickens towards the Ringvassøy-Loppa Fault Complex (Faleide et al., 1993) and also north- and southward before onlapping against the Loppa High and the Finnmark Platform. Shales and claystones dominate, with thin interbeds of siltstone, limestone and dolomite. The marine environments throughout the group are dominated by distal conditions with periodic restricted bottom circulation. Clastic fans built out from the emergent Loppa High, while the Finnmark Platform was a much less pronounced feature (Worsley et al., 1988). The lowermost, mainly Hauterivian, Knurr Formation probably reflects tectonic events both at its base and top, but it is difficult to resolve the sequence boundaries in the seismic data. On the other hand the overlying Barremian Kolje Formation thickens considerably westwards into the Tromsø Basin. The top represents an important seismic marker and has been dated top Barremian in the Hammerfest Basin (Westre., 1984; Berglund et al., 1986). but the wells show that a thin Aptian sequence, when present, belongs to the Kolje Formation and therefore, an Aptian age to this sequence boundary has been assigned (Faleide et al., 1993) The upper, mainly Albian, Kolmule Formation thins westwards in the Hammerfest Basin but attains large thickness in the Tromsø Basin.

The Upper Cretaceous Nygrunnen Group varies considerably in thickness and completeness. It is most complete in the Tromsø Basin where a 1200 m thick shale succession has been drilled while seismic data indicate that the sequence reaches a thickness of 2000-3000 m in rim synclines in the central basin. The wells on the Senja Ridge show a thin upper Cretaceous sequence, reflecting Late Cretaceous structuring and strong salt related subsidence in the Tromsø and Sørvestnaget Basins. Whereas the Tromsø Basin was a depositional centre throughout most of this period, the areas further east were either transgressed only during maximum sea level and/or display only condensed sections of the original sequence (Worsley et al., 1988). The wells show that the Campanian thins from approximately 250 m to less than 50m eastwards in the Hammerfest Basin. Thus, the upper Cretaceous sequence is difficult to resolve in the seismic data east of the Ringvassøy-Loppa Fault Complex. Claystones with thin limestone stringers in the Tromsø Basin and western part of the Hammerfest Basin change into more calcareous or sandy condensed sequences to the east. The claystones were deposited in open marine, deep shelf environments in the Tromsø Basin and on a shallower starved shelf in the east (Worsley et al., 1988).

The Paleogene Sotbakken Group rests unconformably on the Nygrunnen Group and represents an important depositional break at the Cretaceous-Tertiary transition throughout the southwestern Barents Sea (Worsley et al., 1988). The preserved sequences show a late Paleocene (Thanetian) to early/middle Eocene (Ypresian/Lutetian) age in the Hammerfest Basin. The sediments are dominated by claystones and interbedded thin siltstones, tuffs and carbonates deposited on an open to deep marine shelf. The seismic data suggest that the lower part of the group is present throughout the southwestern Barents Sea with little lithologic variation, and that the younger sequences are only preserved in the Tromsø, Harstad and Sørvestnaget Basins. In the deepest part of the Tromsø Basin, the group attains a thickness of more than 2000 m. Within the group, a prominent base Eocene seismic marker, related to the breakup, is developed along the continental margin.

Recent drilling showed that to the northwest of the Hammerfest Basin, Oligocene – Miocene strata were drilled in the Sørvestsnaget Basin and Vestbakken Volcanic Province (Ryseth et al., 2003). Significant marine shallowing took place at the Eocene – Oligocene boundary and shallow marine conditions persisted throughout the Oligocene – Miocene.

The Neogene Nordland Group rests unconformably on Paleogene and Mesozoic rocks, and thickens dramatically towards the west where it forms the major part of the sedimentary wedge along the margin. The sediments are dated as late Pliocene to Pleistocene/Holocene in the Hammerfest Basin where there is little evidence of Miocene and Oligocene sediments (Worsley et al., 1988). In the Neogene, most of Barents Sea was uplifted and eroded (Berglund et al., 1986). In recent years extensive geophysical and geological investigations of the Barents Shelf have revealed the extent of the uplift and erosion and the possible consequences for the reduction of the hydrocarbon potential of the area (Eidvin and Riis, 1989; Nyland et al., 1992; Riis and Fjeldskaar 1992). As a result, the magnitude, timing and causes of the uplift are matters of considerable interest and debate. In particular, the discussion seems to have polarized into two camps; one group of workers advocating a tectonic origin for the uplift, most probably related to the rifting of the continental margin to the west, followed by later subsidence of the shelf. The other group suggests that glacial erosion and overdeepening, associated with isostatically-driven uplift, is the main cause. An important piece of evidences, supporting the latter hypothesis is that the major part of the clastic fan on the western margin of the Barents Sea is of late Pliocene-Pleistocene age, rather than extending back to the mid Tertiary as previously thought (Eidvin & Riis, 1989). This interpretation implies that the sequence of glacial sediments, which is typically 100-200 m thick in the Hammerfest Basin, increasing to more than 700 m at the Senja Ridge, expands to about 4000 m in the Lofoten Basin (Faleide et al., 1996). There is also discussion concerning the magnitude of the Neogene uplift and erosion. An average of 600m of late Cenozoic erosion has been inferred in the western Barents Sea from volume estimates of glacial sediments in the Lofoten Basin (Eidvin & Riis 1989; Vorren et al., l99l). However, local erosion estimates tend to exceed this average: Manum & Throndsen (1978), using vitrinite reflectance studies from sediments of the eastern Central Basin (of Tertiary age) in Svalbard (Spitsbergen), suggested that 1.3-1.7 km of overburden have been eroded. A study in the vicinity of the Svalis Dome and the Maud Basin, (Løseth et al., 1992), indicated 1750-2050 m of total Cenozoic erosion. Finally, a recent study of Dimakis et al., (1998) in the Svalbard-Barents Sea region, has showed high erosion rate up to 1 mm/year, mostly caused by glacial erosion.

2.2. Petroleum system

Source rocks

The exploratory drilling in the Hammerfest Basin has revealed Jurassic and Triassic source rocks of considerable lateral extent. These may have generated significant amount of hydrocarbon in parts of the basin over the last 60 million years.

Upper Jurassic shale of the Hekkingen Formation is the main source rock in the study area, together with the mainly Early to Mid-Triassic shale of the Steinkobbe Formation. Shales of Ladinian and Carnian age are also good candidates.

A summary of the stratigraphical positions of possible hydrocarbon source rocks in the Hammerfest Basin is shown in the Figure 2.6.

Reservoir rocks

The best reservoir rock in the Hammerfest Basin is undoubtedly the Stø Formation of Pliensbachian-Bajocian age. So far most of hydrocarbon discoveries are confined to this formation, though both the Dirøy and the Nordmela Formations also have some reservoir potential (Berglund et al., 1986).

In most wells the Stø Formation overlies the Nordmela Fm. The formation consists mainly of fine- to medium-grained sandstones in the lower part with intervals of large-scale cross-stratification. Very fine to highly bioturbated sands dominates in the upper part which also includes up to three thin mudstone beds. Thin intervals with pebbly sandstones are present within the upper part. Phosphorite nodules are locally present in the uppermost part of the formation.

According to Berglund et al., (1986), source rock intervals can be found mainly in the Nordmela and Oldefjord (up to 20% TOC).

The Stø Formation represents, in general, shoreline and nearshore depositional environments strongly influenced by storm-wave processes and bioturbation. The thick sandstones of the formation represent a complex building or amalgamation of mainly wave-reworked shoreline sediments. The formation reflects several episodes of relative sea-level shift, but there is an overall tendency to more distal marine facies upwards (lower shoreface-offshore) (Berglund et al., 1986).

The sandstones are predominantly quartz-rich in composition, but traces of more feldspathic composition are also found.

Results from recent year's exploration show that other formations also contain sandstone units of good reservoir quality, such as the Knurr and Kolje Formations, from Hauterivian to Barremian age. In the northern part of the Hammerfest Basin significant volumes of sands are proven in deep marine fans.

According to Berglund et al. (1986), the present burial depth (below the sea floor) of the reservoirs in the western Hammerfest Basin is in the range of 1500-2000 m. The porosity is almost 20 vol%. It decreases rapidly with increased burial in the Ringvassøy-Loppa Fault Complex (RLFC), whereas up to 30 vol% is found at 1200 m depth in the Troms-Finnmark Fault Complex (TFFC). The major diagenetic controls on the porosity are mechanical compaction, pressure solution and quartz cementation. Secondary porosity which has been created by grain leaching is of less importance, and the influence of carbonate cement is limited to thin layers.

Recently in 2007, one oil and gas discovery was made in the Southwestern Barents Sea in well 7125/4-1, north-west of the 7122/7-1 Goliat discovery (NPD, 2009). Hydrocarbons were encountered in the Realgrunnen group from the Late Triassic/Early

Jurassic Age and in the Kobbe formation in the Middle Triassic Age. This adds a new level where potential reservoirs could be expected, below the well known Mid Jurassic Stø formation.

The Hammerfest Basin has proven a difficult place to find oil since the exploration began three decades ago. Some 64 wells have been drilled in the Hammerfest, Tromsø and Sørvestsnaget Basins, and on the Loppa High, with all discoveries testifying to the prevalence of gas in the southwestern Barents Sea (Andrew et al., 2006). This is the effect of uplift and erosion which is typical for the peripheral North Atlantic margin basins that have undergone Cenozoic exhumation, mainly thought to have occurred during the Paleocene, Oligocene-Miocene or Pliocene (Andrew et al., 2006). This is main reason of abundant gas and very little oil discovery in the region. The prevalence of gas and lack of significant oil accumulations are thought to be related to an episode of major exhumation during the Cenozoic (Corcoran and Doré., 2002).

3. Data and methods

Over the three decades of oil exploration in the southwestern Barents Sea, a large amount of seismic data has been acquired and some 80 wells have been drilled (GeoExpro, 2009). In some areas, the data coverage is extremely dense, witnessing the intense activity developing within this vast underexplored region, including the Loppa High and the Hammerfest Basin.

In this thesis work, regional 2D seismic lines and a 3D survey are used, together with data from two wells.

3.1. Seismic data

The data used in this study are represented in the base map constructed in PETREL and showed in the Figure 3.1. The 2D seismic reflection data are from five different surveys: AN88, SG9715, LHSG-89, NH8306 and TTR-lines. The total length of the 2D lines is about 5900 km. In general, the 2D lines are good and the recording time is up to 6 s TWT. Compared to the others, the LHSG-89 survey has a poorer resolution when displayed in PETREL. The color and the gain had to be adjusted on these lines in order to improve the quality of the image. Moreover, some from the initial database of the lines were not used because the image they display is distorted in PETREL. But when displayed in GEOFRAME or KINGDOM, the same lines have no problems.

In addition, a 3D survey of 70 633 km total length which covers the north-eastern part of the study area is showed in red on the base map (Figure 3.1).

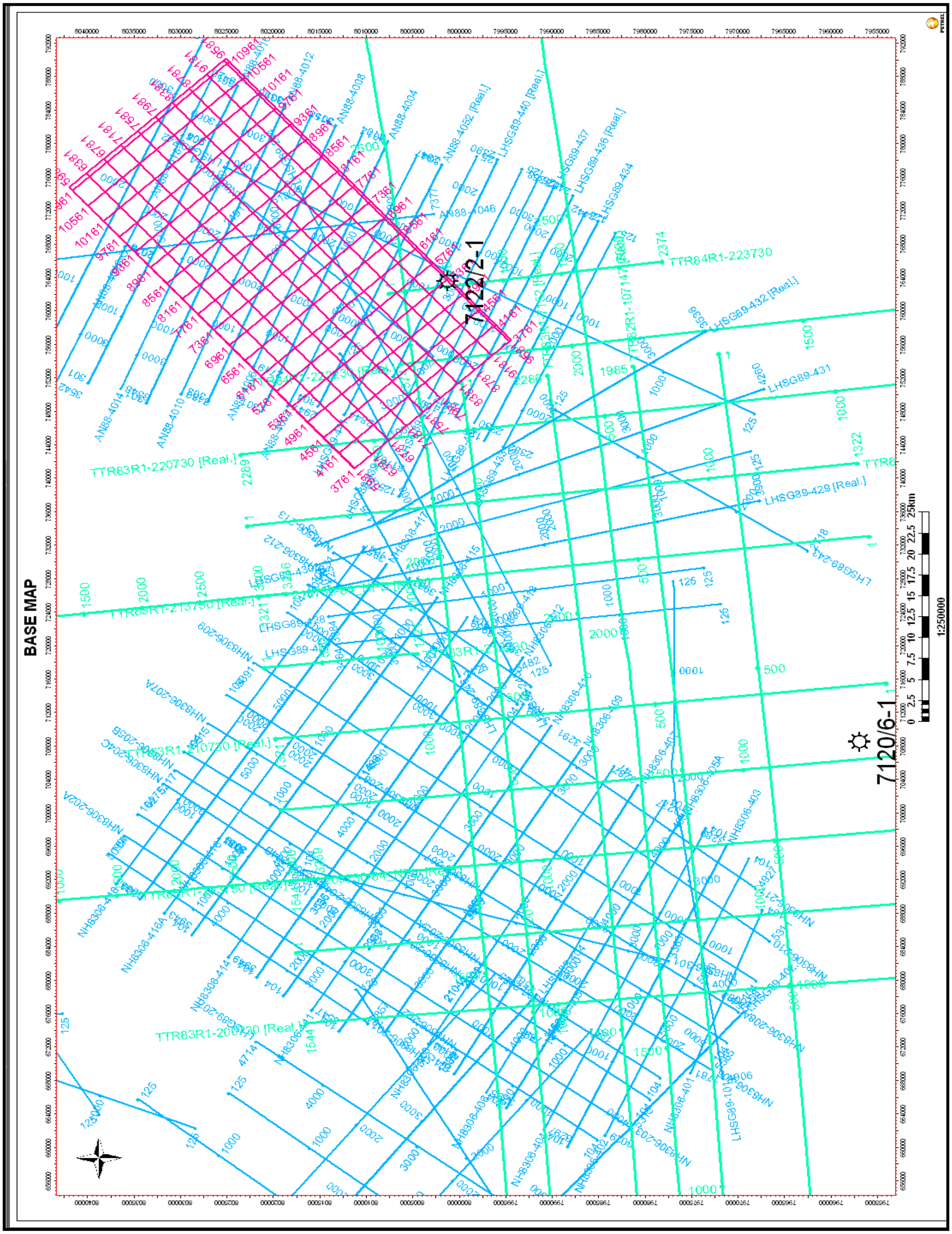


Figure 3.1. Base map of the study area showing the 2D lines (blue and green), the 3D cube (red) and well location.

An overview of the seismic data is given in table 3.1 below.

Survey	Type	Client name	Shot by	Area	Year	Length (km)
AN88-9Q6-1	2D	AMOCO	GEOTEAM	N.KAPPB.SO	1988	617.03
AN88-9Q6-2	2D	AMOCO	GEOTEAM	FINNM. ØST	1988	121.584
AN88-9Q6-3	2D	AMOCO	GEOTEAM	DIA EAST	1988	140.747
AN88-9Q6-4	2D	AMOCO	GEOTEAM	LOPPA PLAT	1988	1 166.724
SG9715	2D	SAGA	NOPEC	BARENTS SE	1997	488.297
NH8306	2D	HYDRO	GECO	TROMSØFLAK	1983	1 512.604
LHSG-89	2D	STATOIL	GECO	LOPPA.SYD	1989	1 802.492
					Total 2D lines	**5 849.478**
SG9803	3D	SAGA	GECO	FELT 7223	1998	70 632.472
					Total	**76 481,95**

Table 3.1. Summary of the different surveys constituting the seismic database (Modified from NPD.no)

3.2. Well data

Two wells, both located in the Hammerfest Basin (Figure 3.1), have been used in this study.

The first one, the Exploration well 7120/6-1 was drilled in the Snøhvit field in 1985 in the middle-eastern part of the block down to the Late Triassic Tubåen Formation at a depth of 2820 m.

The well encountered hydrocarbon bearing Jurassic sands of the Stø Formation from 2385.5 m to 2469.5 m. The interval from 2385.5 to 2427 m was gas bearing and from 2427 to 2443 m oil bearing. In the interval 2559 - 2800 m (Tubåen Formation), thin gas bearing sandstone stringers were encountered. This interval spanned the Jurassic-Triassic boundary, and in the lower intervals below 2660 m net pay was associated with thin interbedded coals. Weak oil shows were observed in claystones in the Cretaceous below 2176 m. Good oil shows in sandstones were recorded throughout the hydrocarbon bearing zone and down to 2500 m. Below this level oil shows were in general associated either with mudstones or with coal seams and fragments.

Well 7122/2-1 is located on the northern periphery of the Hammerfest Basin towards the Loppa High. Drilled in October 1992, this well reached the Stø Formation at 2120 m and was dry.

Lithostratigraphic information from these two wells has been used as well tops during the interpretation procedure (Table 3.2).

Well 7120/6-1		**Well 7122/2-1**	
Top depth [m]	**Lithostratigraphic unit**	**Top depth [m]**	**Lithostratigraphic unit**
337	NORDLAND GP	386	NORDLAND GP
410	SOTBAKKEN GP	418	SOTBAKKEN GP
410	TORSK FM	418	TORSK FM
1081	NYGRUNNEN GP	743	NYGRUNNEN GP
1081	KVEITE FM	743	KVITING FM
1117	ADVENTDALEN GP	764	ADVENTDALEN GP
1117	KOLMULE FM	764	KOLMULE FM
1843	KOLJE FM	1764	KOLJE FM
2176	KNURR FM	1832	KNURR FM
2285	HEKKINGEN FM	1955	HEKKINGEN FM
2367	FUGLEN FM	2025	FUGLEN FM
2386	KAPP TOSCANA GP	2068	KAPP TOSCANA GP
2386	STØ FM	2068	STØ FM
2470	NORDMELA FM	386	NORDLAND GP
2559	TUBÅEN FM	418	SOTBAKKEN GP

Table 3.2. Well Tops used in the study.

3.3. Methodology and approach

In order to familiarize with the study area and understand the main structural aspects of the Hammerfest Basin and the Loppa High, the study started with a regional seismic interpretation of selected 2D seismic sections on paper (220730; 215230; 213730; 210730; 205230; 203730; SG9715-401). These seismic lines interpreted on paper are shown in green in the Base Map (Figure 3.1).

The next step after this preliminary work was to map out on paper the main structural features in the study area. This task was very useful and necessary because it enhanced the understanding of the different structures framing the area and also their extent.

Then, the interpretation was carried out on a workstation using the PETREL software, firstly in 2D. At this stage, the objective was to map out the main seismic reflectors, together with the main boundary fault and the local faults, using seismic sequence stratigraphy method. From this, few keys lines which reflect the different aspects of the Hammerfest Basin and the Loppa High were selected for the construction of chronostratigraphic charts.

Finally, the constructed chronostratigraphic charts were used for the reconstruction of the geological history of the study area.

4. Seismic interpretation

A major part of the present thesis is based on the interpretation of regional 2D seismic lines. Less work has been carried out on the 3D seismic data. This can be explained by the main goal of the thesis, which is to make a synthesis of the evolution of the Hammerfest Basin during Late Jurassic – Early Cretaceous times. One of the best ways to proceed was to interpret 2D regional lines which cover the study area entirely and map out the main structural features as shown in Figure 4.1. Applying seismic stratigraphy for the interpretations, regional profiles were produced and used as basis for the construction of chronostratigraphic charts. Detailed analysis of the chronostratigraphic charts was then the next step in the reconstruction of the geological history of the study area.

4.1. Interpretation procedures

Some of the seismic lines composing 2D surveys were interpreted on paper: 215230; 213730; 210730; 205230; 203730; SG9715-401 and 7200. Most of these are North-South oriented lines which run from the Hammerfest Basin to the Loppa High, across the Asterias Fault Complex (Figure 1). They are the most appropriated to study the geometry and the geological aspects of the study area.

The same lines were used as a basis to start the interpretation on workstation using PETREL, in particular the line 205230, utilizing previously published interpretations (Faleide et al., 1993 and Gudlaugsson et al., 1998). The idea was to interpret this line and use it as a starting point for interpretation and correlation of the main seismic sequence boundaries on the other lines. The nearby well 7120/6-1 was tied to this line for a control on the seismic sequences (Figures 4.2). The formation tops from the well were then used in the interpretation of the western part of the study area, from the well location towards the Ringvassøy-Loppa Fault Complex in the west, by using composite lines and crossing-lines as guides from the line 205230.

The same procedure was repeated for the eastern part of the study area, with well 7122/2-1, tied with the line LHSG-440 as illustrated in Figures 4.3 and 4.4.

Finally, the interpretation of the rest of the area was carried out by correlating the well tops between the two wells.

In parallel, a map was produced, showing the extent of the eroded surface on the Southern flank of the Loppa High which is believed to be the source area from where sediments are deposited in the Hammerfest Basin (Figure 4.1). The area is covered by a dense network of 2D and 3D lines, illustrating its importance for oil exploration. Indeed, this is an area where one would expect to find different types of traps, structural and stratigraphical. Part of the Asterias Fault Complex is shown on the map. The faults have an overall E-W direction, before changing to NE-SW direction and dies out in the northeastern part of the study area. A limit of the Lower Cretaceous sediments which are pinching out on the flanks of the Loppa High is also displayed (Figure 4.1). This mapping process helped to understand the main structural features in the study area and the relationship between them.

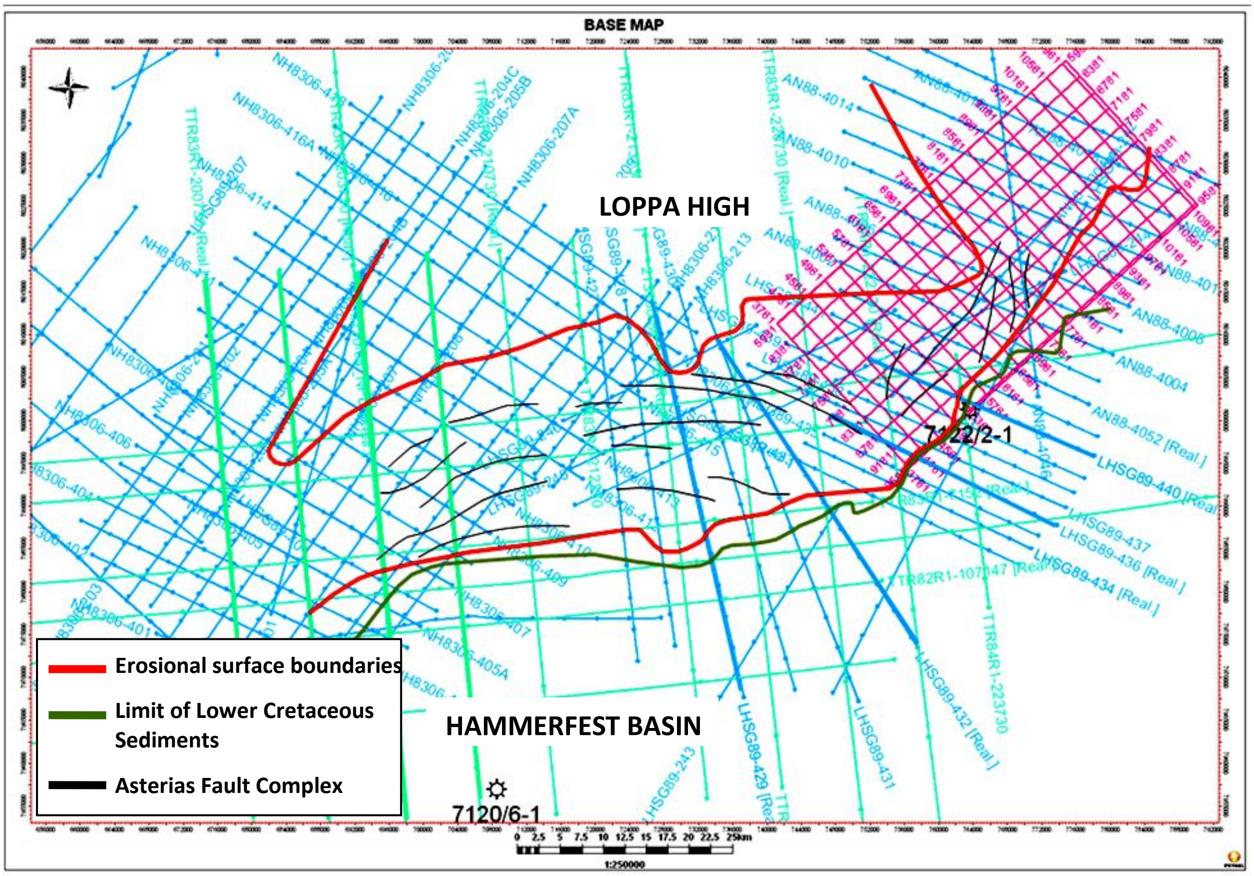


Figure 4.1. Map of main faults and erosional surface on southern flank of the Loppa High.

4.2. Seismic to well ties

In this study, the correlation was done for each of the two wells 7120/6-1 (Figure 4.2) and 7122/2-1 (Figures4.3 and 4.4), respectively tied with the closest seismic lines, 205230 and LHSG89-440. Both wells are located in the Hammerfest Basin (Figure 4.1).

The well 7120/6-1 was drilled in the Central Eastern part of the Basin, down to Lower Jurassic Tubåen Formation at 2820 m depth, and located at about 2 km away from the line 205230. The second well 7122/2-1 was drilled in the northern periphery of the Hammerfest Basin towards the Loppa High, with a TD at 2120 m in the Middle Jurassic Stø Formation. This well is located at some 730 m distance from line LHSG89-440.

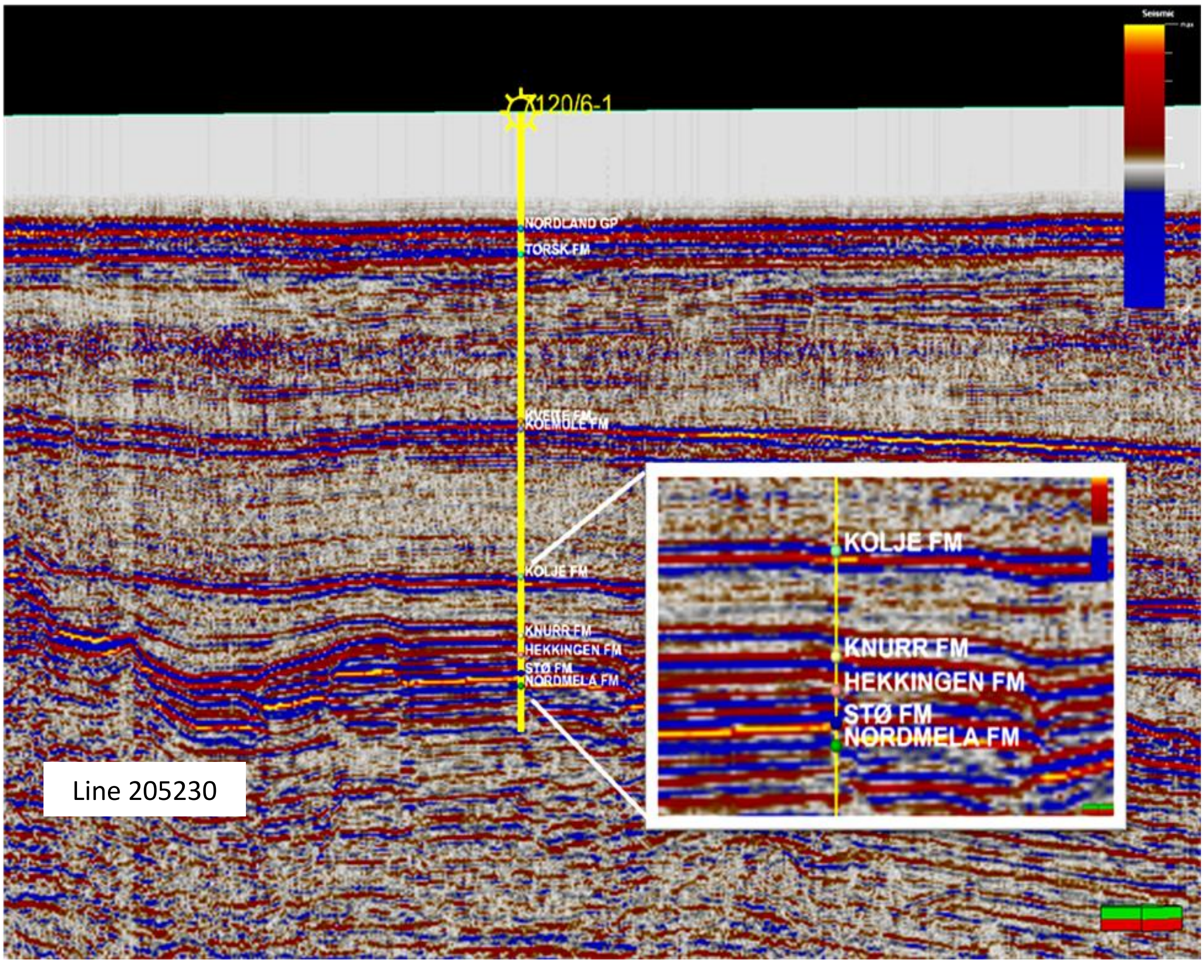


Figure 4.2. Calibration of the line 205230 with the well 7120/6-1.

The calibration of line 205230 was done by correlating the well tops and the seismic boundaries on the section (Figure 4.2). For this well, log data could not be displayed in the same manner as for the other, because only the well tops were available.

Figure 4.3 shows an example on how each seismic sequence on the Line 7122/2-1 was tied by correlating its boundaries with the picks from the well tops. In addition, well logs such as the Gamma Ray Log and the Density Log were displayed along with the seismic section to help us identify the reflectors. A close-up view is shown in Figure 4.3.

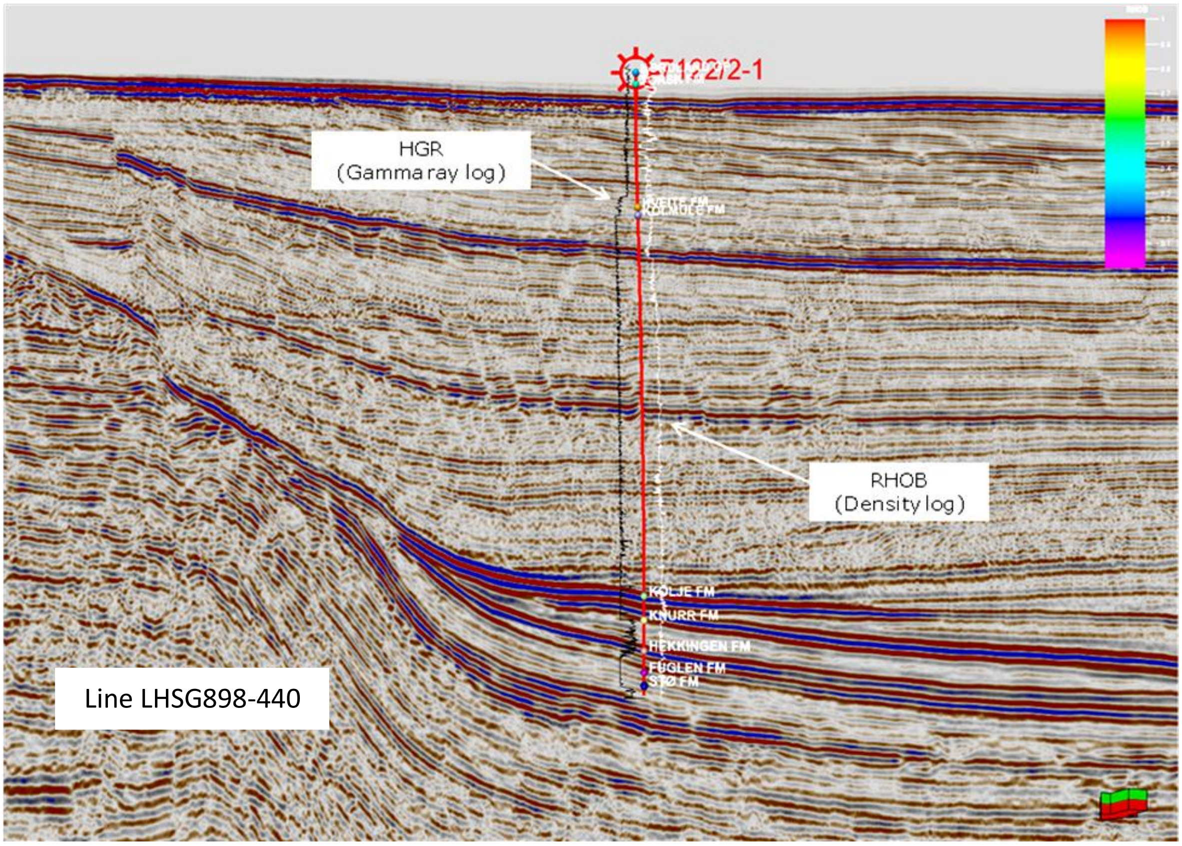


Figure 4.3. Calibration of the seismic section LHSG89-440 with well logs from well 7122/2-1.

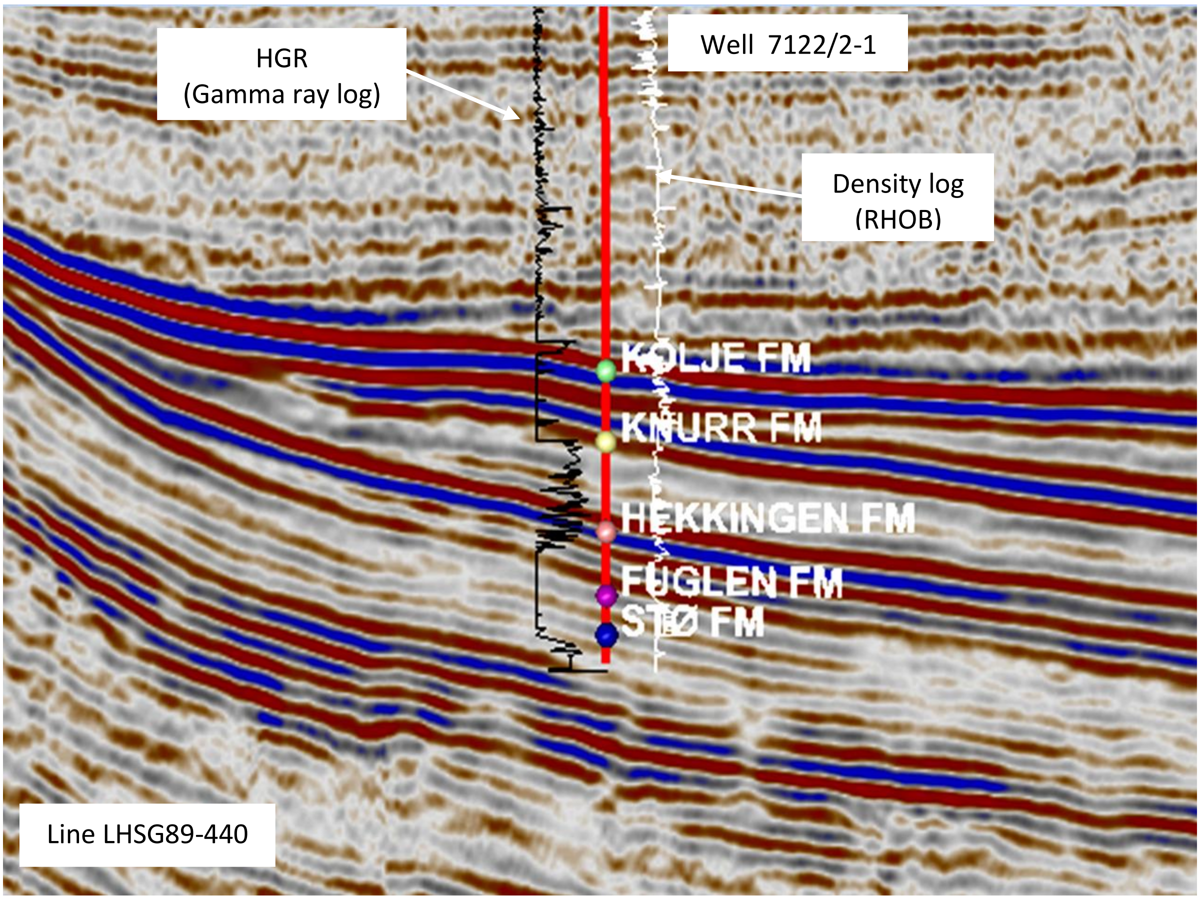


Figure 4.3. Close-up of tie between line LHSG89-440 and well 7122/2-1.

4.3. Seismic sequence stratigraphic framework

In the south-western Barents Sea the main seismic sequences correspond to major lithostratigraphic units (Faleide et al., 1993). In total, six reflectors have been interpreted and assigned different colors as shown in Table 4.1.

The main focus in this thesis work is the time interval from Late Jurassic to Early Cretaceous. Five seismic sequence boundaries were selected: Middle Jurassic, Base Cretaceous, Hauterivian and Aptian within the above mentioned time interval and also Base Tertiary. The Upper Triassic boundary was interpreted for the needs of the study. Furthermore, this reflector will be used as a reference surface, particularly because it is one of the strong and good continuous reflectors, which can be traced along the different profiles.

Reflector	Age	Color
Top Kolmule Fm (6)	Base Tertiary	
Top Kolje Fm (5)	Top Barremian	
Top Knurr Fm (4)	Top Hauterivian	
Top Hekkingen Fm (3)	Base Cretaceous	
Top Stø Fm (2)	Late Middle Jurassic	
Snadd Fm (1)	Intra Upper Triassic	

Table 4.1. Main reflectors interpreted and their color code.

A description of the different reflectors interpreted is provided. The seismic line 205230 is used as a reference line (Figure 4.5).

Intra Upper Triassic

On the Loppa High, The Upper Triassic reflector was picked within the Snadd Formation. The reflector shows strong amplitude, high frequency, high continuity and gently dips towards the Asterias Fault Complex. It is the oldest surface interpreted in this study. The Upper Triassic surface is affected by the complex faulting which cuts the area of the Loppa High in series of horsts and grabens. The interpretation of the Upper Triassic reflector was particularly difficult because of the height of the vertical throw across the Asterias Fault Complex (about 1750 ms TWT), and its correlation into the Hammerfest Basin (Figure 4.5) is difficult without well control. The reason is that on the basin side, this reflector looks totally different: the amplitude strongly decreases from the main boundary fault and the reflector gradually becomes discontinuous towards the crest of the dome which forms the center of the Hammerfest Basin. All of this makes it difficult to recognize the Intra Upper Triassic reflector.

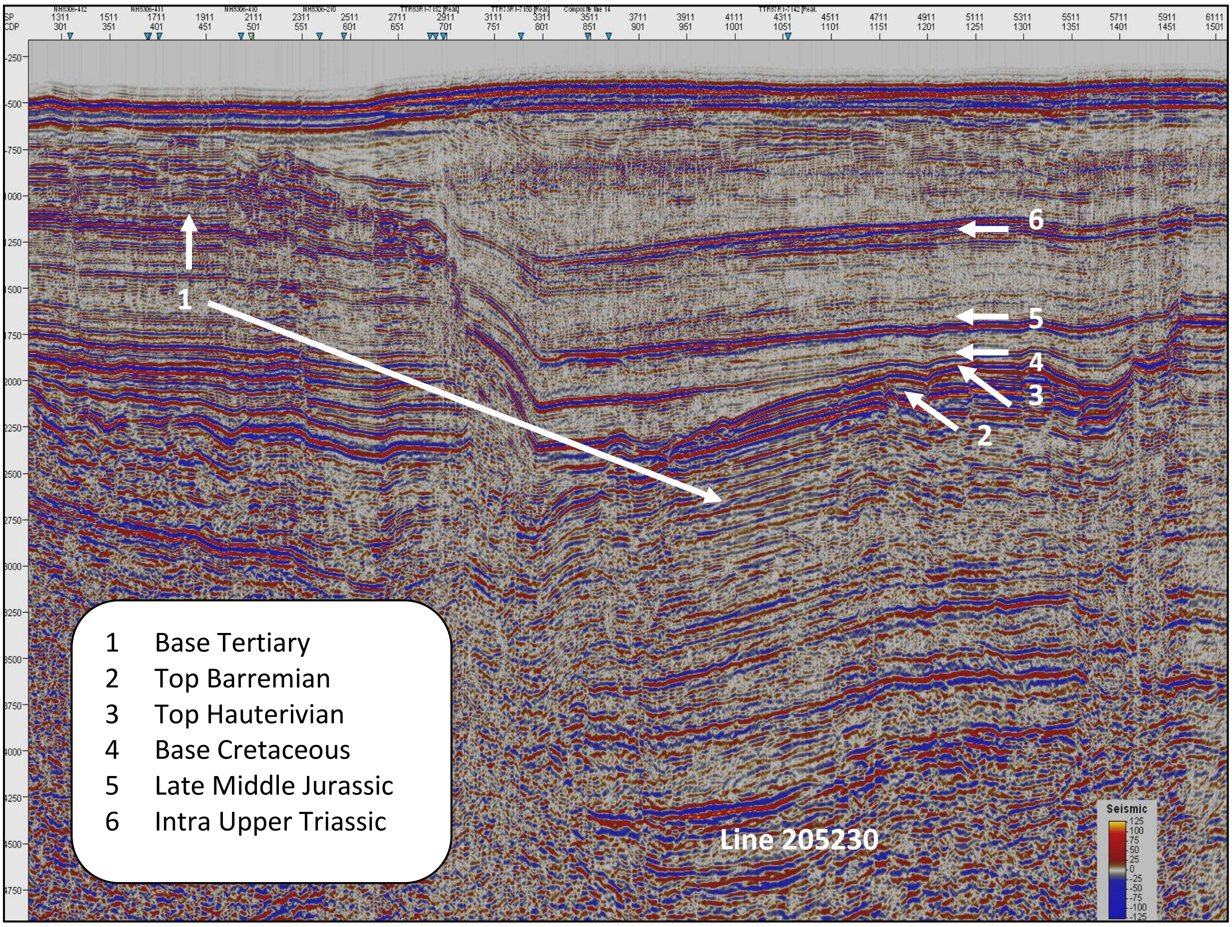


Figure 4.5. Main seismic sequence boundaries interpreted.

None of the two wells available in this study have reached this reflector. So we rely to the interpretation and indications from other workers in the same area in our interpretation of the Upper Triassic seismic boundary. A third well 7120/8-2 was drilled in the central area of the Hammerfest Basin, close to the east-west main fault that divides the dome structure in two. Although it has reached the Late Triassic Fruholmen Formation, data from this well were not used for calibration purpose because it is located at a great distance (about 17 km) from the end of the lines to be correlated.

The Intra Upper Triassic reflector is the base of the seismic sequence number 1, as illustrated in the Figure 4.6. This lowermost sequence includes the upper part of the Snadd Formation and the four formations which compose the Realgrunnen Group: Fruholmen Formation, Tubåen Formation, Nordmela Formation and Stø Formation. The sequence is disrupted by the Asterias Fault Complex. It shows parallel, laterally consistent internal reflections in the Loppa High whereas in the Hammerfest Basin, the consistence and the continuity decreases towards the center and the eastern part of the basin and also in the areas close to the boundary fault where the pattern becomes chaotic and complex. Parallel and laterally consistent reflections are the signature of pre-rift sequences.

Late Middle Jurassic (Top Stø Formation)

The Late Middle Jurassic reflector represents the top of a sandstone sequence. In the western part of the Hammerfest Basin where the reference line is located, this reflector is restricted within the basin. It also represents the basal boundary of the Teistengrunnen Group (Figure 4.6). The reflector has a high amplitude, high frequency and high continuity and can be situated at 2050 – 2550 ms TWT.

The seismic sequence overlying Late Middle Jurassic surface was called sequence 2. It is composed by the Fuglen and the Hekkingen formations. The Fuglen Formation was included in sequence 2 although it is separated by a hiatus from the Hekkingen Formation. The reason is because in seismic we have to deal with the problem of vertical resolution such in the case of the Fuglen Formation which is too thin and the hiatus is not very important (Figure 4.6).

In the western part of the study area, the seismic sequence 2 is affected by a set of normal faults in the tilted faulted blocks. Moreover in these areas, the sequence 2 shows divergent internal reflection pattern. In this case, the above indicated normal faults called growth faults are an expression of extensional movements during a rifting phase. Sequence 2 is then determined as a syn-rift sequence.

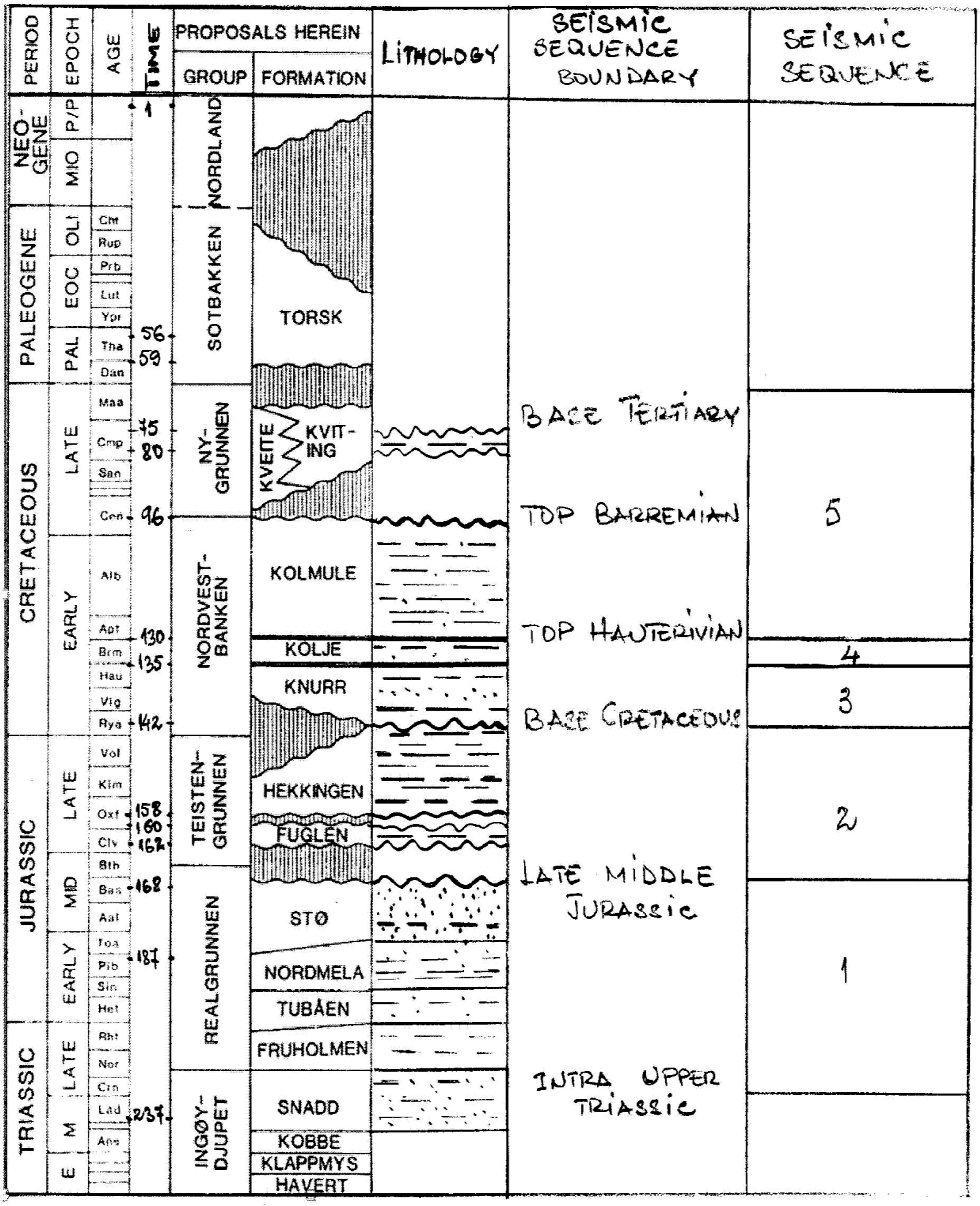


Figure 4.6. Seismic sequence stratigraphic framework.

Base Cretaceous (Top Hekkingen)

This reflector corresponds to the base of the Lower Cretaceous Nordvestbakken Group which comprises three formations: the Knurr, Kolje and Kolmule formations (Figure 4.6). Marked by a hiatus, Base Cretaceous surface is a strong reflector with medium to high amplitude and high frequency which could easily be followed throughout the Hammerfest Basin. This reflector can be picked at 1750 – 2400 ms TWT.

The Sequence 3 is found above the Base Cretaceous reflector. This sequence lies on top of the underlying sequence with a small hiatus (Dalland et al., 1988). Generally the internal reflectors have low amplitude, low frequency and low continuity. This means overall uniform deposition energy. In the western zone of the area, the sequence thickens towards the flanks of the basin but at the same time it thins from the west to east. The reflections show two different directions depending on the area. In the western part, they are on laping the flanks of the central dome, while from the flexure zone to the east, large lenses can be seen in the proximal part. Whereas the distal part has the same parallel reflections.

Following the shape of the underlying Late Middle Jurassic reflector, sequence 3 is very thin in center of the Hammerfest Basin and thickens towards its northern flank. Internal reflectors are onlaping on the surface of the dome structure and show an overall low amplitude sequence. In the Central and the Eastern zone of the study area, this sequence is onlapping and pinching out on the basin slope.

Top Hauterivian (Top Knurr)

The Top Hauterivian reflector corresponds to the top of the Knurr Formation, which also thins at the centre of the Hammerfest Basin while it thickens considerably towards the northern flank of the basin. The Top Hauterivian surface can be found between 1550 – 2150 ms TWT. It is a reflector with low to medium amplitude and frequency.

Seismic sequence 4 lies above the Top Knurr surface. The reflections in this sequence are parallel-even to sub-parallel. This seismic sequence follows the overall characters of the underlying one: thinning towards the crest of the central dome and also from the west to the east. In this area the proximal part is represented by single large lens with low amplitude and frequency. The sequence pinches out on the flank of the slope almost at the same point.

Top Barremian (Top Kolje)

The Barremian reflector marks the top of the Kolje Formation. It has a medium to high amplitude, low to high frequency and medium to high continuity. The Top Barremian is situated at 1100 – 1900 ms TWT.

Lying directly above the Top Kolje surface, sequence 5 is the thickest in the succession. Parallel to subparallel reflections are generally observed in the distal part of the sequence but the lateral continuity varies from high to low. The amplitude varies from low to medium with some areas exhibiting high amplitude in the western edge of the basin (Line 200730, Figure 4.7). The amplitude decrease is more emphasized from the central flexure zone and to the east.

Base Tertiary

The Base Tertiary reflector is the youngest interpreted. It is a continuous reflector and corresponds to the boundary between Paleocene and the underlying Cretaceous strata. The Upper Cretaceous Kveite Formation is generally very thin or absent, so sequence 5 mainly comprises the Kolmule Formation of Aptian to mid Cenomanian age (Figure 4.6). The reflector exhibits a medium to high amplitude with low to high frequency and can be followed at 750 -1350 ms TWT. The main boundary fault dies out within the Tertiary sequences.

In the northern flank of the Hammerfest Basin, all the above described surfaces have some common characters: from the basin center they dip gently northwards before shallowing towards the flank of the Loppa High.

Except the special case of correlation of the Upper Triassic reflector, all the reflectors interpreted are quite identifiable over the Hammerfest Basin.

4.4. Interpretation of regional 2D seismic lines

From the 2D seismic database, 9 North-South trending regional profiles were selected after an assessment prior to the seismic interpretation as shown further in this chapter. The lines were chosen along the strike of the Hammerfest Basin from West to the East. The criterion for the selection was to cover the entire study area and also to show the lateral changes in the structure of the basin from the western to the eastern part of it, through the central zone where the Asterias Fault Complex changes direction and morphology. Therefore, the study area was divided in three zones:

- Western zone (200730, 202230, 203730, 205230);
- Central zone (LHSG89-429, LHSG89-432);
- Eastern zone (LHSG89-433, LHSG89-436, and LHSG89-440).

In some of the lines, the erosional surface on the Loppa High is displayed in red to show its extent. This surface was mapped and can be seen in the figure 4.1. Interpreted key lines are shown in bold.

4.4.1. Western zone

Line 200730

This N-S section is located in the westernmost part of the Hammerfest Basin. It shows an area where the Loppa High is deeply buried below thick Cenozoic units and morphologically consists of a crest controlled by a horst (Figure 4.7).

The study area is divided in two by the boundary fault separating the Loppa High and the Hammerfest Basin: the Asterias Fault Complex which is seen between 640-500 CDP.

The dome structure which forms the internal part of the Hammerfest Basin is partly seen on the section. This structure is affected by a series of dominantly E-W trending normal faults. From the central part of the basin, sedimentary units dip toward the Asterias Fault Complex where they end up with a normal drag. In this part of the basin, the subsidence along the main boundary fault was continuous.

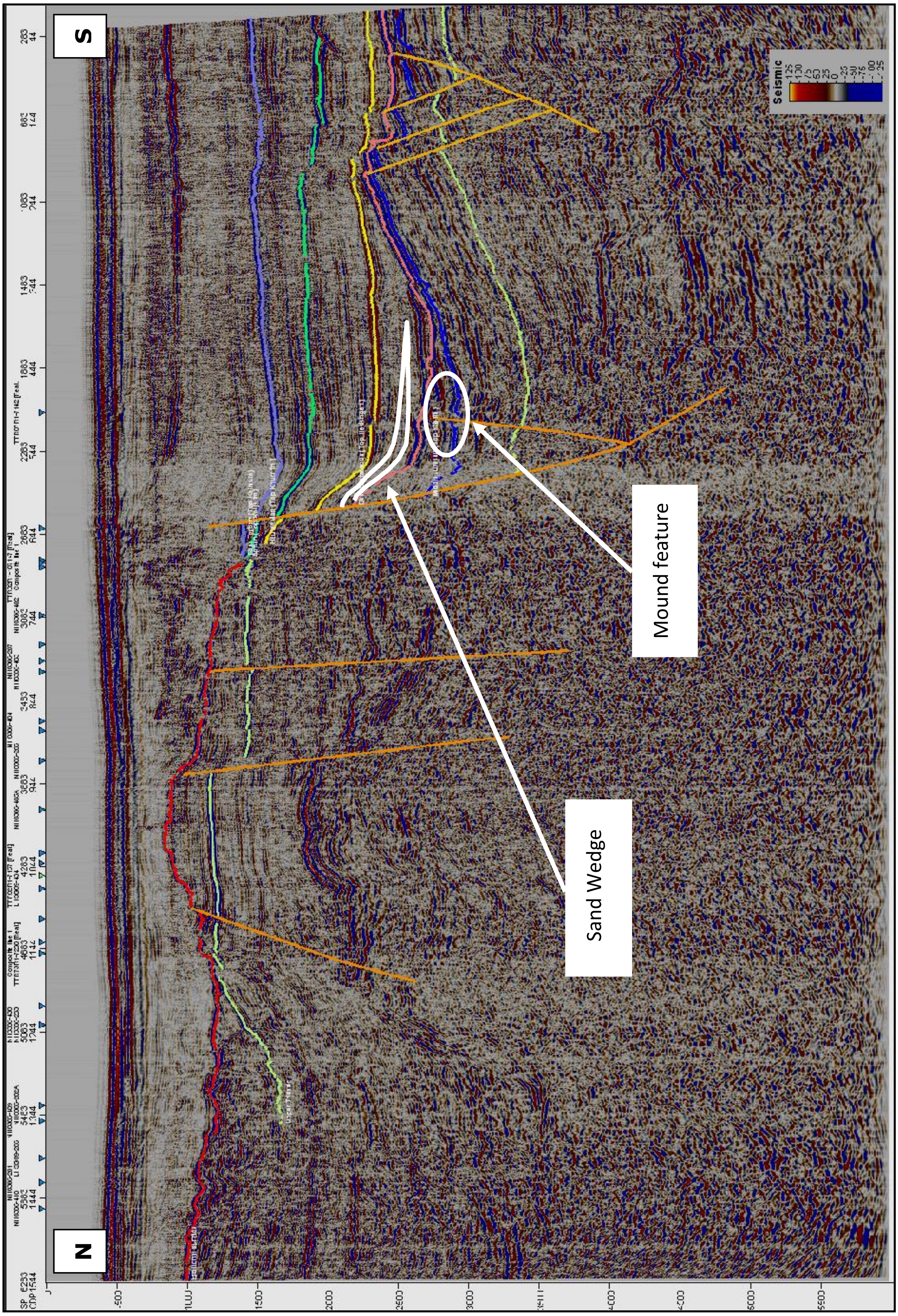


Figure 4.7. Line 200730 trending N-S, see Figure 4.1 for line location.

Sequence 4 (Kolje Formation) which was faulted during the Paleocene and sequence 5 (Kolmule Formation) are both onlaping the flanks of the Loppa High, while the shelf was subaerially exposed and shows the relief of erosional unconformity, before the deposition of the Tertiary sediments.

A mounded feature is observed within the seismic sequence 2 (Figure 4.9), located in the deepest part of the sequence on the profile, towards the main boundary fault. This mound feature represents a basin floor submarine fan deposited during an early lowstand stage. This feature is affected by the Paleocene faulting.

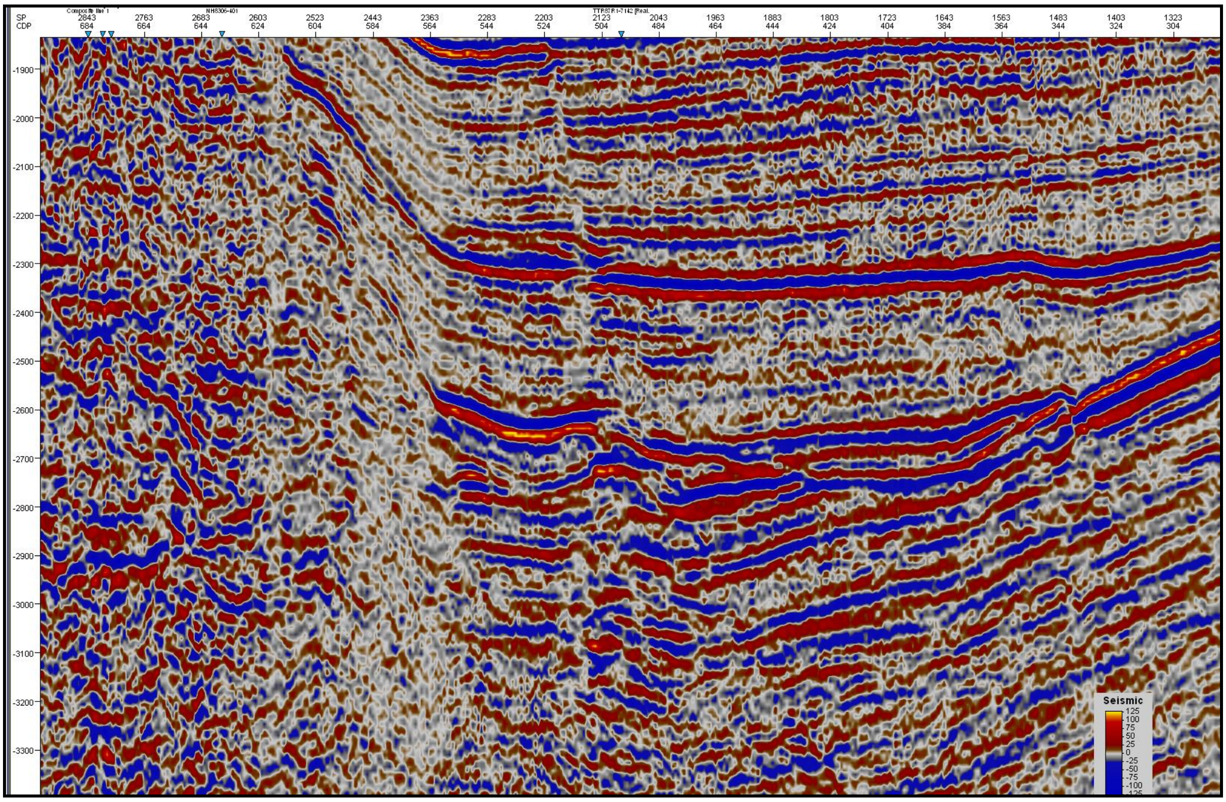


Figure 4.8. Close-up view of Line 200730 showing a mounded feature located at 2680-2920 ms TWT interval, CDP 532-472.

A sand wedge is also observed within the same Formation (Figure 4.8), building out from the flanks of the Loppa High.

The individual clinothems in sequences 2 and 3 are onlapping on the northern flank of the central dome. This structure was totally covered by the sediments by the end of Hauterivian times.

Line 202230

Line 202230 shows a different context in the transition from the Loppa High to the Hammerfest Basin. In this section, an inversion of the tectonic movements in the Paleocene time along the Asterias Fault Complex is observed, overprinting normal faulting, from subsidence to uplift. This can be seen from the reverse drag showed by the different units along the fault complex, from Upper Triassic to Tertiary strata. As a result, the boundary fault becomes more complex and an intermediate positive structure was formed between the Loppa High and the Hammerfest Basin (Figure 4.9). A subbasin was created along the northern flank of the Hammerfest Basin. This intermediate dome structure is interpreted as an expression of the second round of uplift movements which affected the study area. All the units from the Upper Triassic up to Paleocene was deformed and folded during this second faulting.

A broad shelf with a flattened surface formed on the Loppa High as a consequence of these vertical movements, feeding at the same time the Hammerfest Basin with the erosional products. Prograding successions with clinoforms can be seen in Late Paleocene sediments from the Loppa High but their thickness has significantly decreased compared to the previous seismic section 200730 (Figure 4.8). This means that the Hammerfest Basin is a syn-tectonic basin fed by the uplift of the Loppa High and possibly the Finnmark Platform.

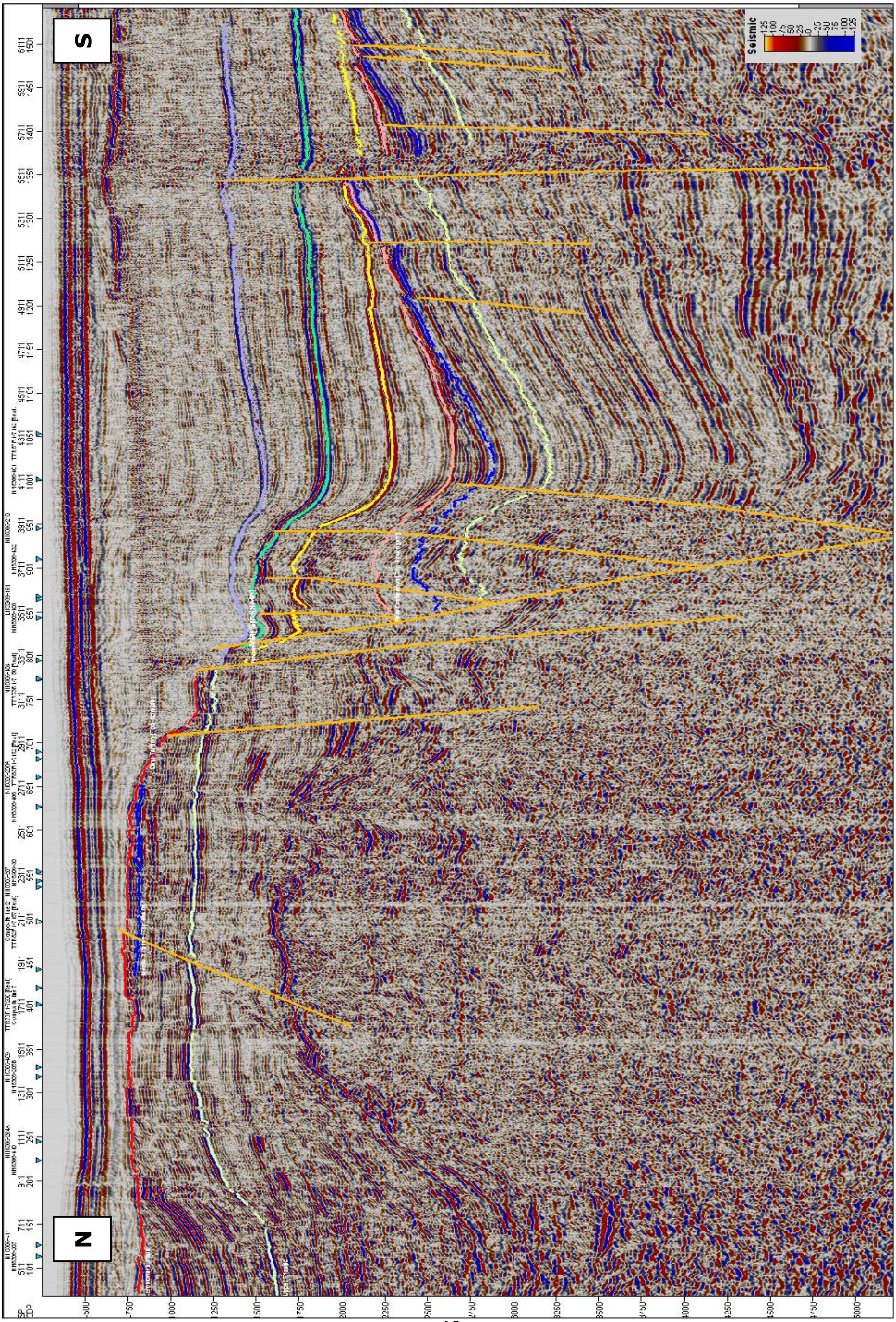


Figure 4.9. Interpretation of the N-S trending Line 202230. See Figure 4.1 for line location.

Line 205230

Line 205230 is one of the longest available and shows almost the entire Hammerfest Basin (Figure 4.10). The observed uplift from the interpretation of the previous line still can be seen but less marked than in this section. The erosion of the shelf zone is more the deepest in the area, the Lower Jurassic sediments are truncated by the Paleocene unit which lies directly above them.

A thickening of the Upper Triassic sediments is noticed across the Asterias Fault Complex. This can be explained by the fact that prior to the formation of the Hammerfest Basin, the area of the Loppa High was a depocenter in Late Triassic times.

The slope of the shelf margin looks less steep on this section and the two Lower Cretaceous units (Kolje and Kolmule formations) are onlaping far on the Loppa High, reaching almost the top of the eroded flank of the Loppa High.

4.4.2. Central zone

Two lines were selected to illustrate the structural change that occurs within this central zone of the study area (Figure 4.1).

Line LHSG89-429

The main change which can be noticed in this section is the nature of the Asterias Fault Complex which gradually dies out in this area and becomes a flexure deforming the Upper Triassic unit and the sediments lying above (Figure 4.11). The lateral continuity of the Upper Triassic reflection is observed all along the section. Huge and deep canyons cutting the shelf area on the Loppa High are also seen, modifying its relief. The difference of the thickness of the Upper Triassic sediments from the Loppa High to the Hammerfest Basin is more visible. Several sand wedges which build out from the Loppa High are observed within the sequence 5 (Kolmule Formation). Some of them are shown in the Figure 4.11 and Figure 4.12.

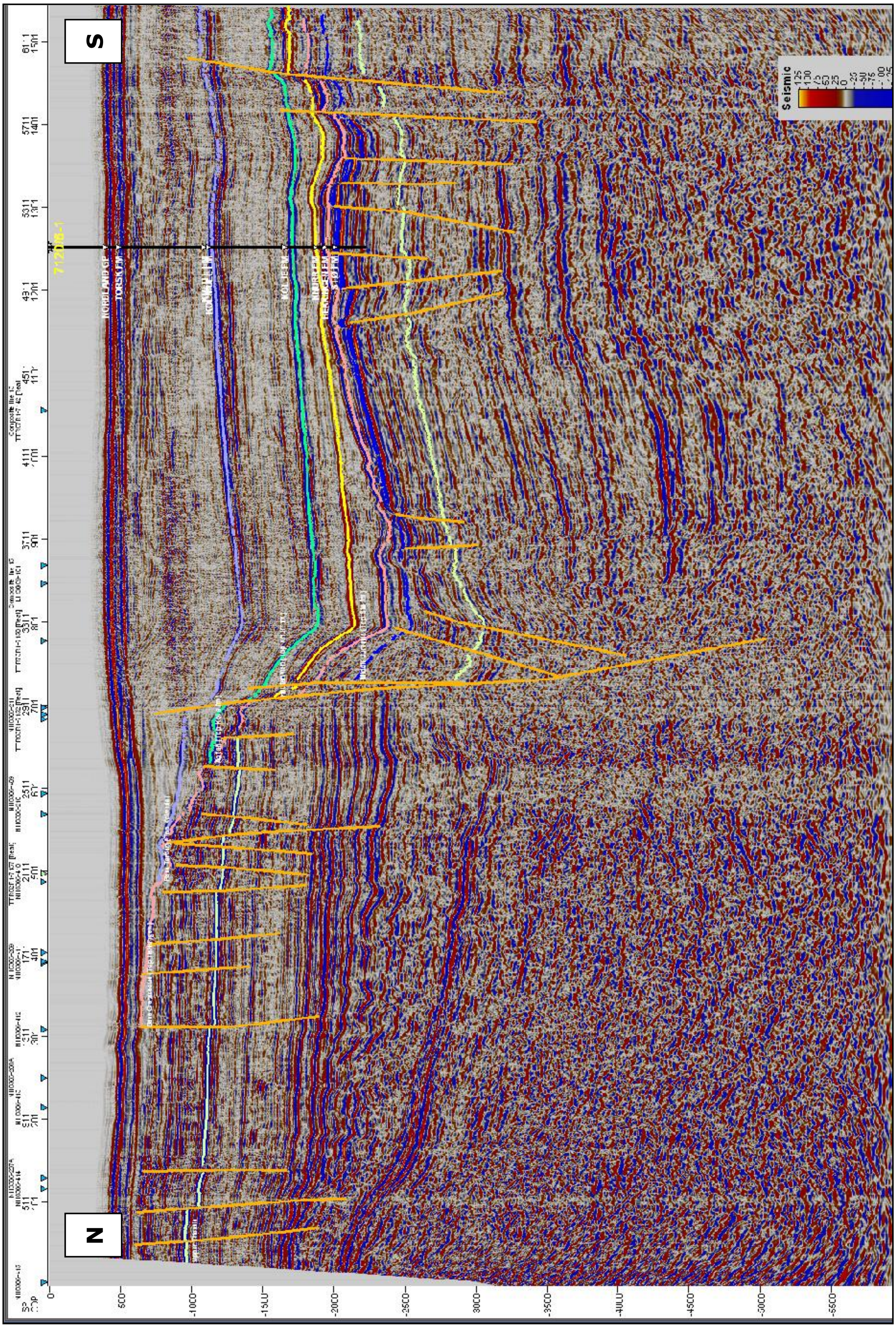


Figure 4.10. Interpretation of the N-S trending Line 205230. See Figure 4.1 for line location.

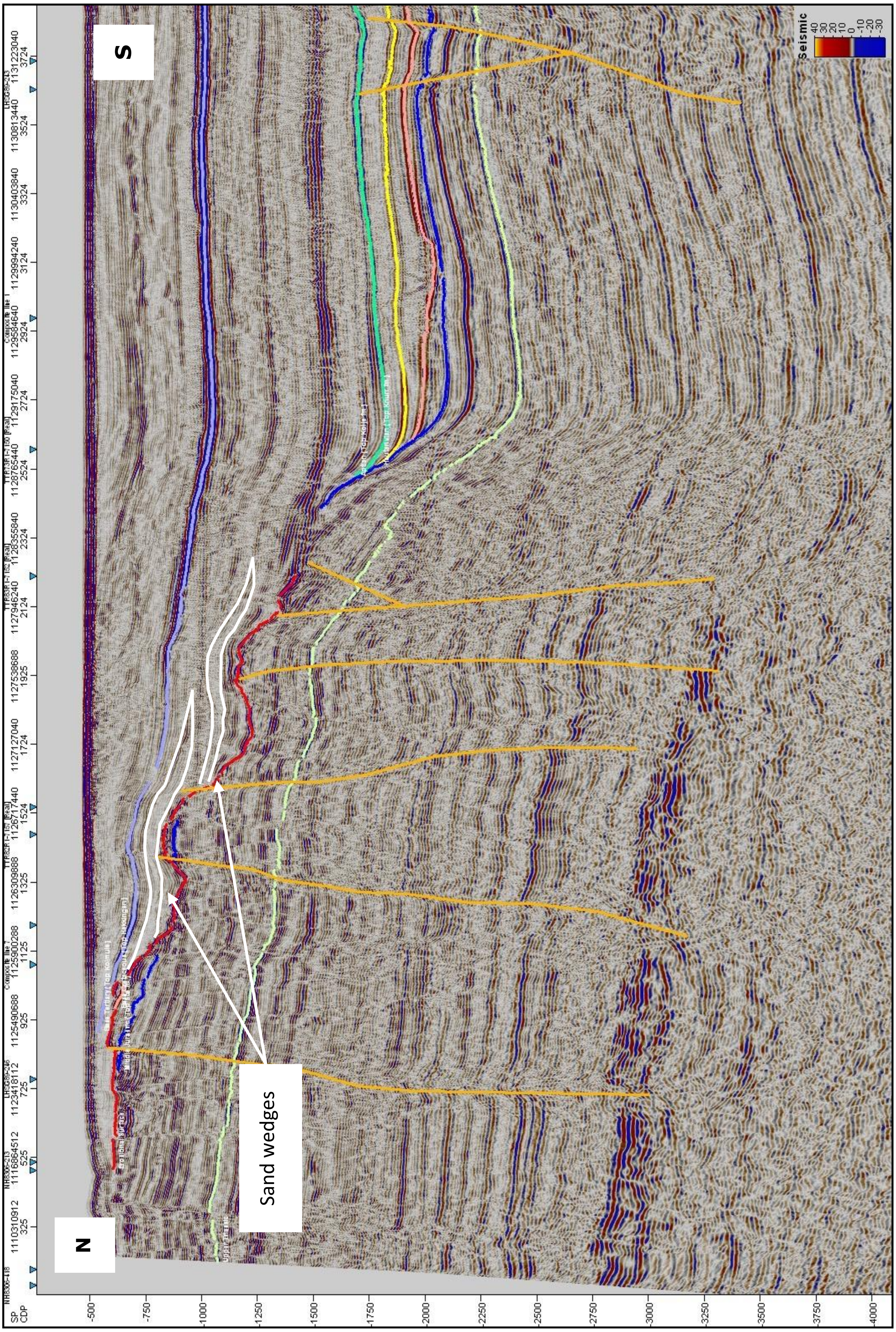


Figure 4.11. N-S Line LHSG89-429 located in the central flexure zone. See Figure 4.1 for line location.

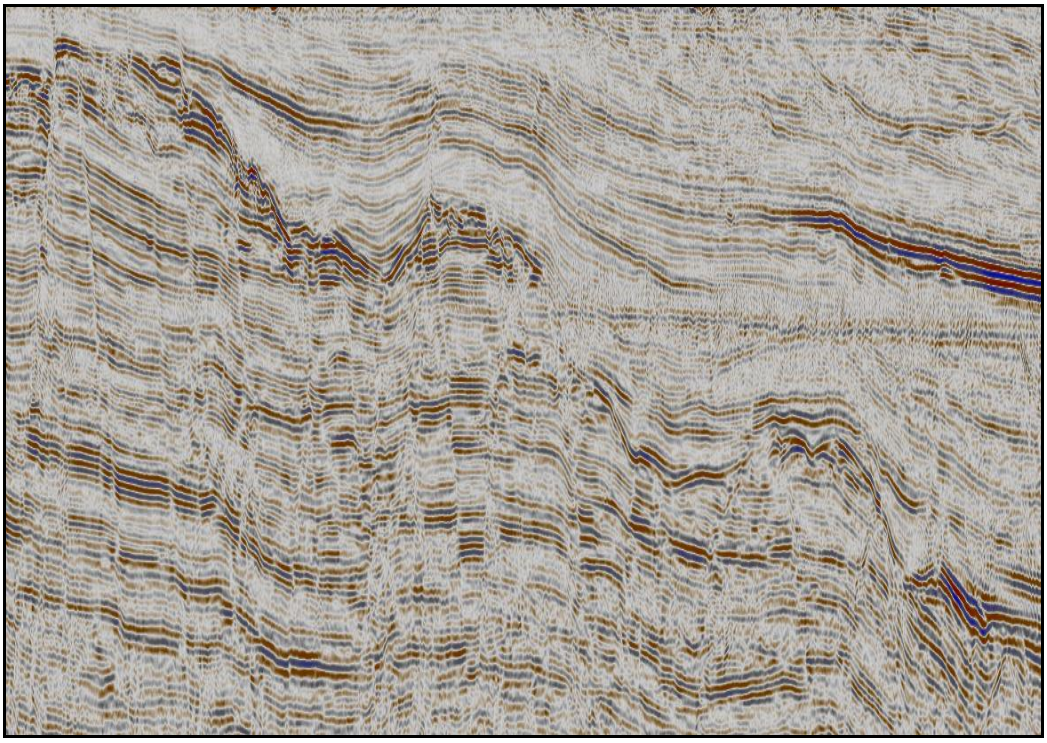


Figure 4.12. Close up view of line LHSG89 showing sand wedges.

Line LHSG89-432

Figure 4.13 shows the interpretation of line LHSG89-432. In this section, the transgression of the Lower Cretaceous sediments over the Loppa High is complete. The area is dislocated by a complex faulting, which resemble to the ones seen on the western side of the study area. A case of a marine onlap is observed in the upper part of sequence 5. The top of this sequence is truncated by the Paleocene sediments. The thinning of the Upper Triassic formation is more obvious.

At the base of the shelf slope, a mounded feature representing a toe of slope fan is observed (Figure 4.13) in sequence 2. The feature seems to be stacked on top of a previous one, which was formed the older sequence 1.

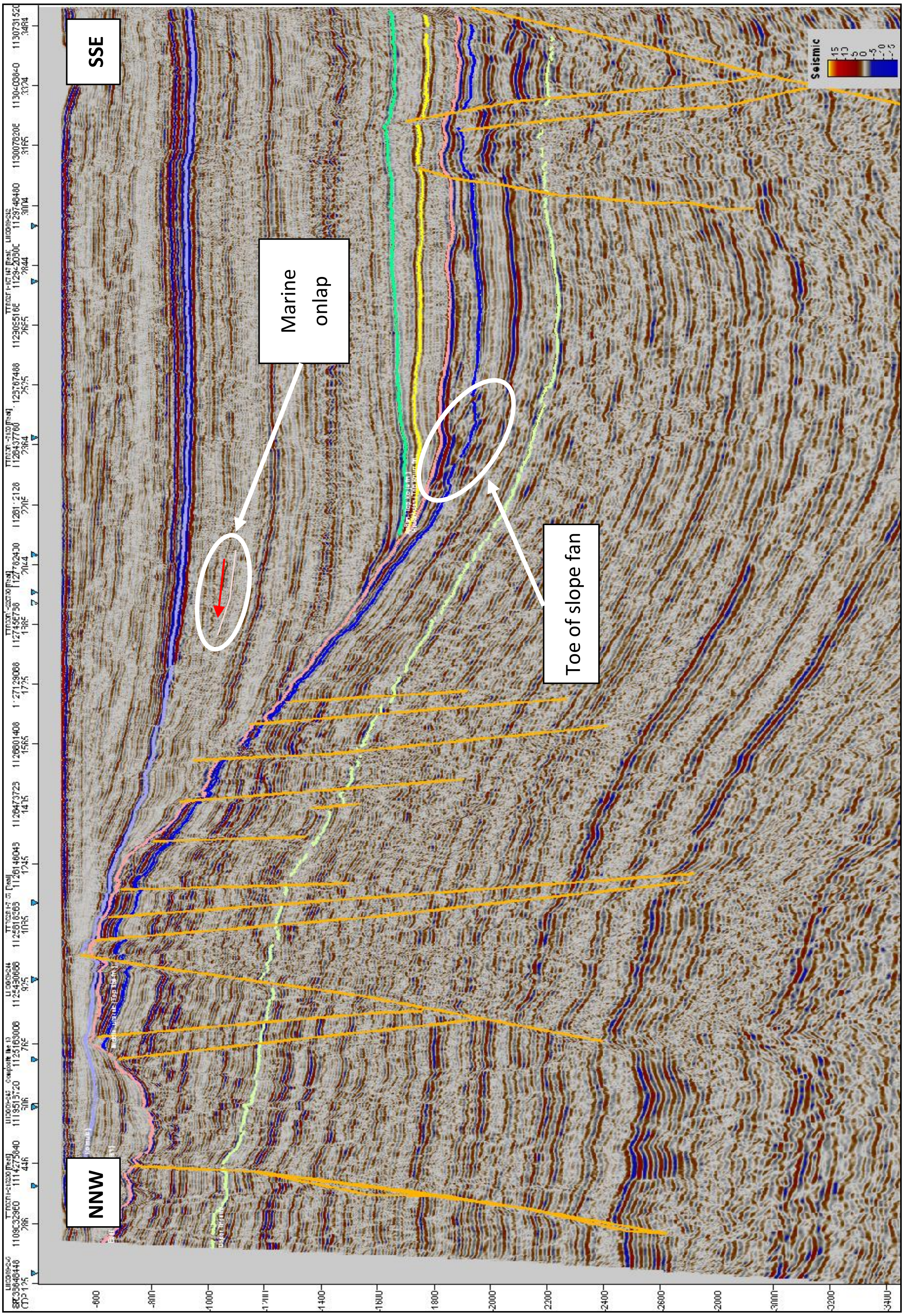


Figure 4.13. Interpretation of the NNW-SSE trending line LHSG-432. See Figure 4.1 for line location.

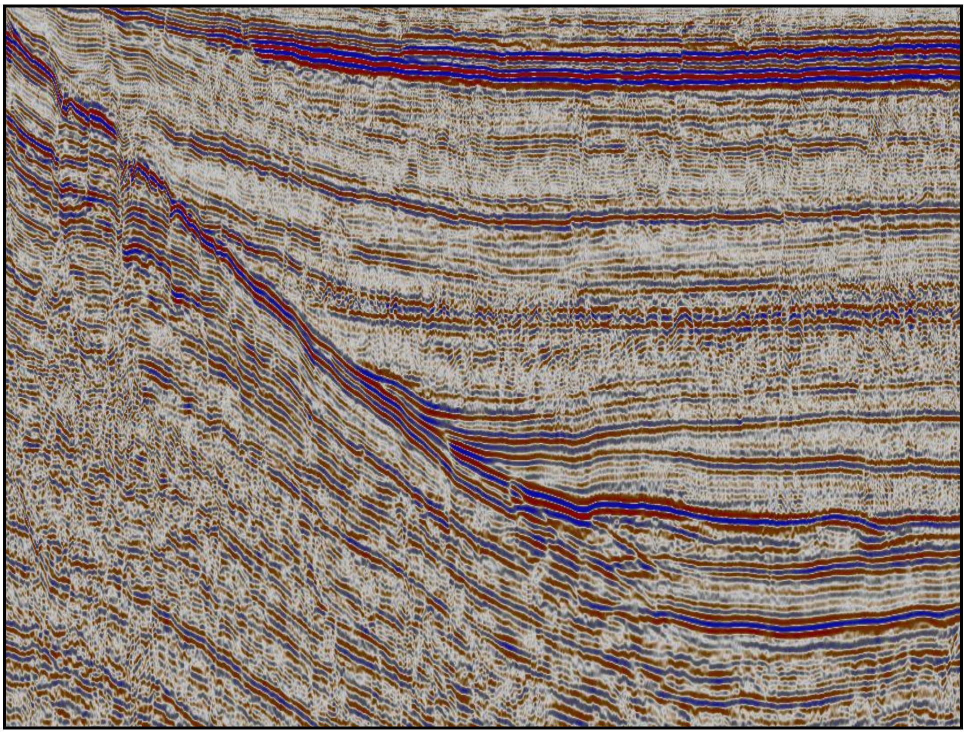


Figure 4.14. Close up view of line LHSG89-432 showing interpreted features toe of slope fan and marine onlap.

4.4.3. Eastern zone

Line LHSG89-440

This line was acquired with a trend of WNW-ESE, following the change in direction of the Asterias Fault Complex (Figure 4.1). Here, the Asterias Fault Complex has a vertical throw, observed by the displacement of the Intra Upper Triassic reflector. A sand lens is seen within the sequence 3 (Knurr Formation) while wedge shaped features are still building out from the flank of the Loppa High. An example is shown in the interpretation of the line LHSG89-440 (Figure 4.15). The wedge displayed was faulted by the reactivation of the Asterias Fault Complex during the Tertiary.

An ocean-bottom multiple cuts through the Aptian units, visible at about 1000 ms TWT, making the analysis of the internal reflection pattern of the formation difficult in this area.

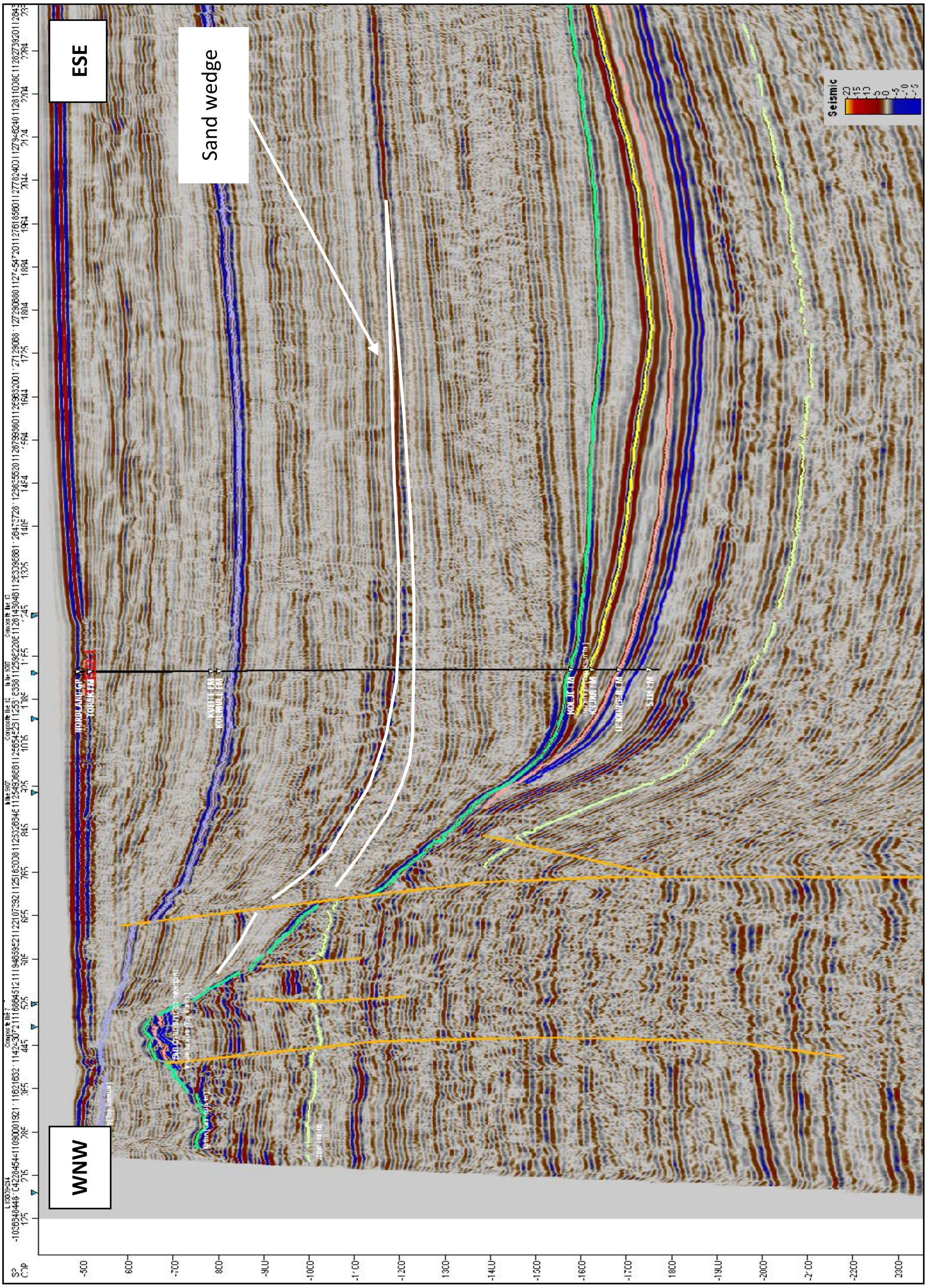


Figure 4.15. Interpreted Line LHSG89-440 trending WNW-ESE. See Figure 4.1 for line location.

A thin remnant part of the eroded lowermost Cretaceous unit is seen on top of the marginal high at around 650 ms TWT. This witnesses that the Base Cretaceous sediments have been deposited at least on a part of the Loppa High surface, before the area was uplifted, tilted and eroded.

4.5. Chronostratigraphic charts

On the basis of the previous seismic interpretation, three profiles were selected for the construction of chronostratigraphic charts. The profiles are selected from different part of the study area, from West to the East, in order to look at the morphology of the basin and also to look at the possible variations of the sedimentation along the strike of the Asterias fault Complex which separates the Hammerfest Basin and the Loppa High. The selected seismic lines are: 205230; LHSG89-432 and LHSG89-440 (Figure 4.1).

The first line 205230 is located in the western part of the Hammerfest Basin, an area where the influence of the Asterias Fault Complex is the most pronounced. Here the Asterias Fault Complex strikes in an E-W direction and shows a maximum throw of about 1500 ms TWT.

The second selected line is located further to the East in the central part of the basin, within a transitional zone where the morphology of the Asterias Fault complex gradually changes from an extensional normal fault to a flexure. This change is accompanied by a change in strike direction from E-W to NE-SW. And finally, the last line is located in the eastern part of the Hammerfest Basin. Here the easternmost segment of the Asterias Fault Complex strikes in a NE-SW direction.

The lithostratigraphy used for the construction of the present chronostratigraphic charts is based on the lithostratigraphical scheme from the "NPD-Bulletin N°4" (Dalland et al., 1988) and the "Lithostratigraphic Lexicon of Svalbard" (Dallmann – 1999). Whereas the time used in the study for age determination is from "A Geological Time Scale" (Gradstein et al., 2004).

The chronostratigraphic charts produced from the three profiles (Figures 4.16 – 4.18) reflect the same geological history; the difference is in the lateral extent of the Jurassic and the Cretaceous sediments which varies from one profile to another, from the west to the east. This lateral variation is due to the morphology and the shape of the Loppa High during the deposition of the different sequences. On line LHSG89-432 (Figure

4.17), the upper part of sequence 5 (Kolmule Formation) starts to overlap the marginal high on the Loppa High. Whereas on the line LHSG89-440 (Figure4.18), the thickness of the Cenomanian sediments overlying the marginal high increases, completing the transgression on the Loppa High.

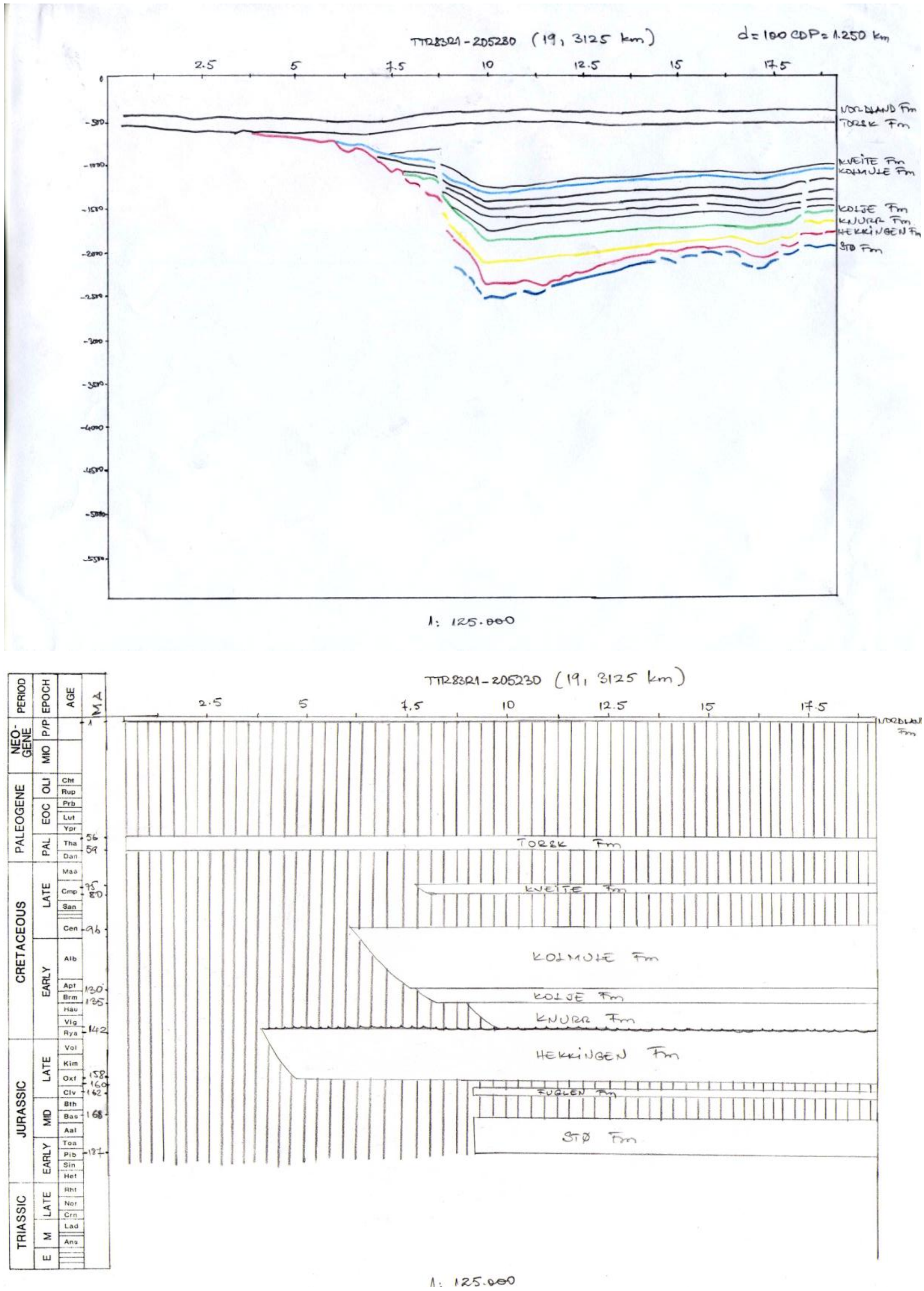


Figure 4.16. Chronostratigraphic chart. Profile 205230.

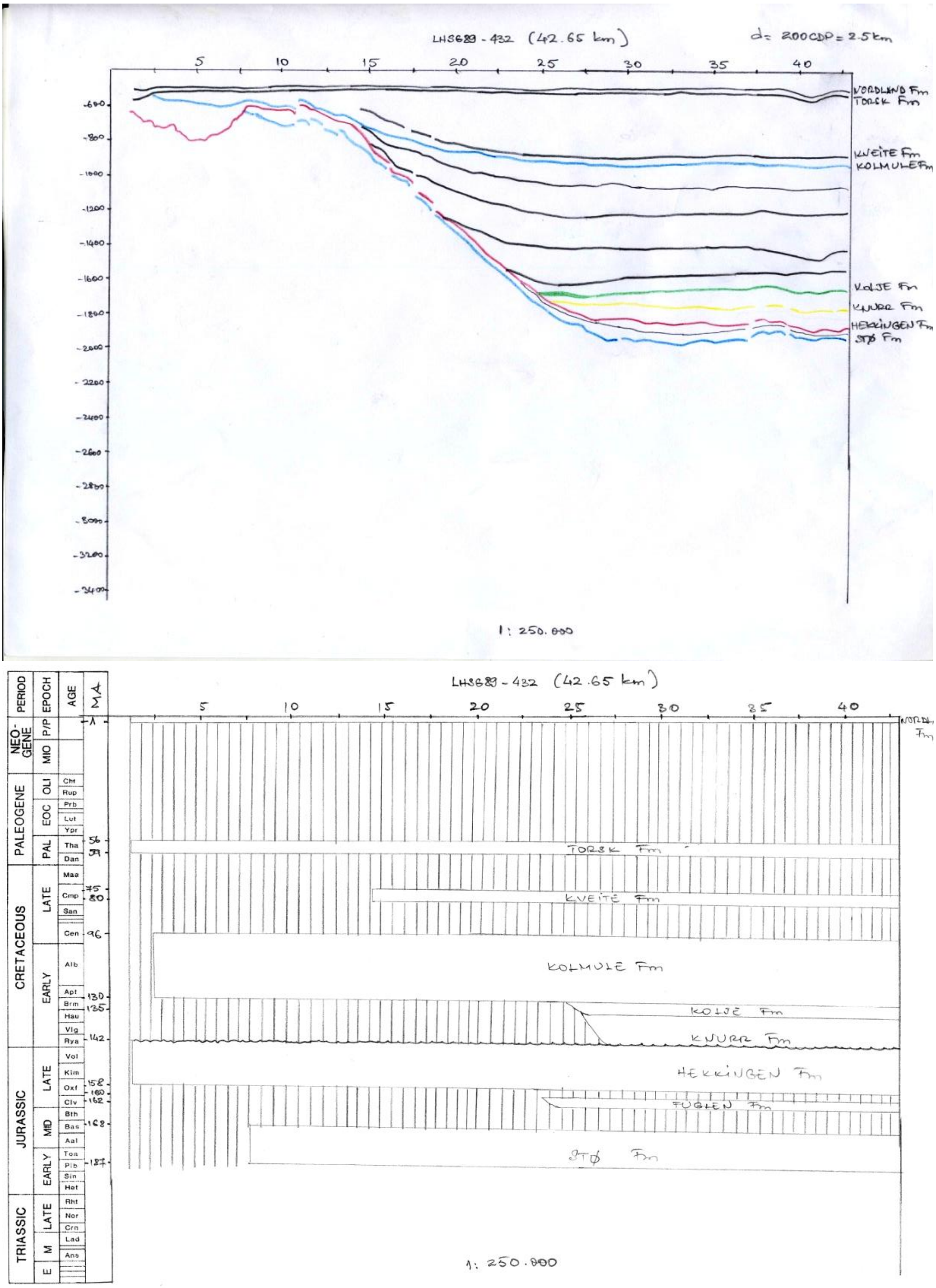
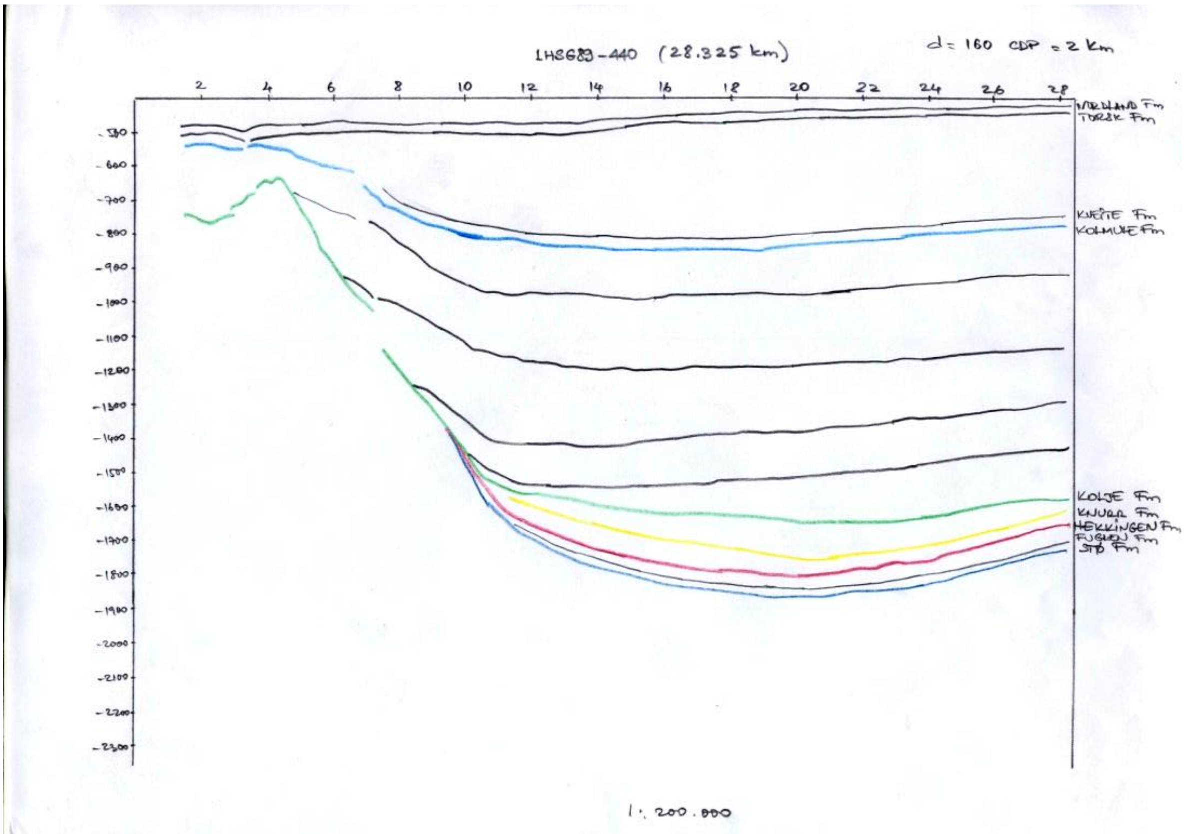


Figure 4.17. Chronostratigraphic chart. Profile LHSG89-432.



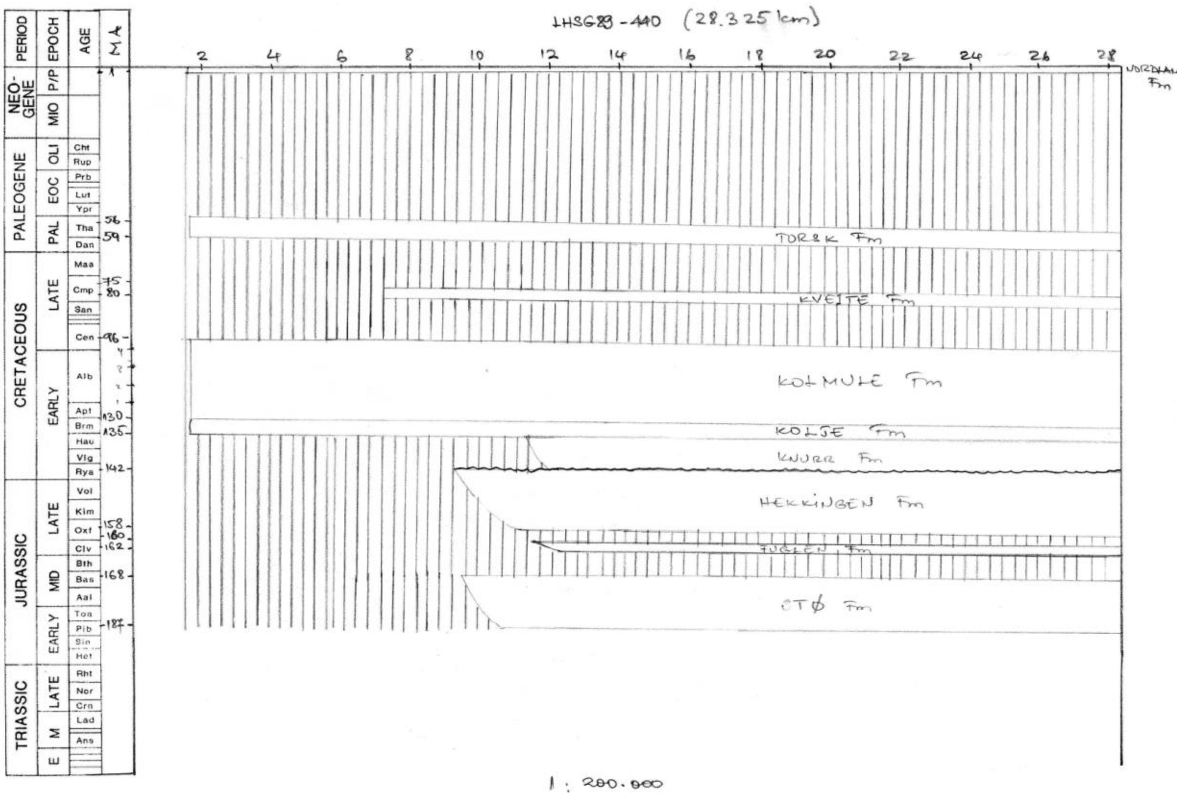


Figure 4.18. Chronostratigraphic chart. Profile LHSG89-440.

The figures above show those periods of non-deposition and erosion in the succession cover the major part of the geological time, compared to the relative short periods of accumulation of the different sequences which took place mostly from Middle Jurassic to Early Cretaceous times. During this period, the subsidence which occurred following the rift stage created accommodation space for sediment supply.

The extent of sediment accumulation in the Hammerfest Basin is controlled by the shape and the morphology of the Loppa High.

Two main hiatuses can be seen in the Hammerfest Basin in the Late Jurassic times. A short time interval of non-deposition also separates the top of the Hekkingen Formation to the base of the Knurr Formation. The first hiatus took place during the Bajocian-Callovian times from 168 Ma to 162 Ma separating the top Stø Formation and the base Fuglen Formation. The second one occurred from 162 Ma to 160 Ma between the top of the Fuglen Formation and the Base of the Hekkingen Fm. These hiatuses are interpreted to correspond to the uplift movements raising the Loppa High at that time; meanwhile the Hammerfest Basin underwent doming.

4.6. 3D seismic interpretation

A 3D seismic cube was loaded for interpretation in the eastern part of the study area, to look more closely at the sediments such as sand wedges and lenses that build out from the slope of the Loppa High, through the deep canyons observed in 2D that are possible entry points.

The extent of the 3D seismic survey SG9803 is showed on Figure 4.19.

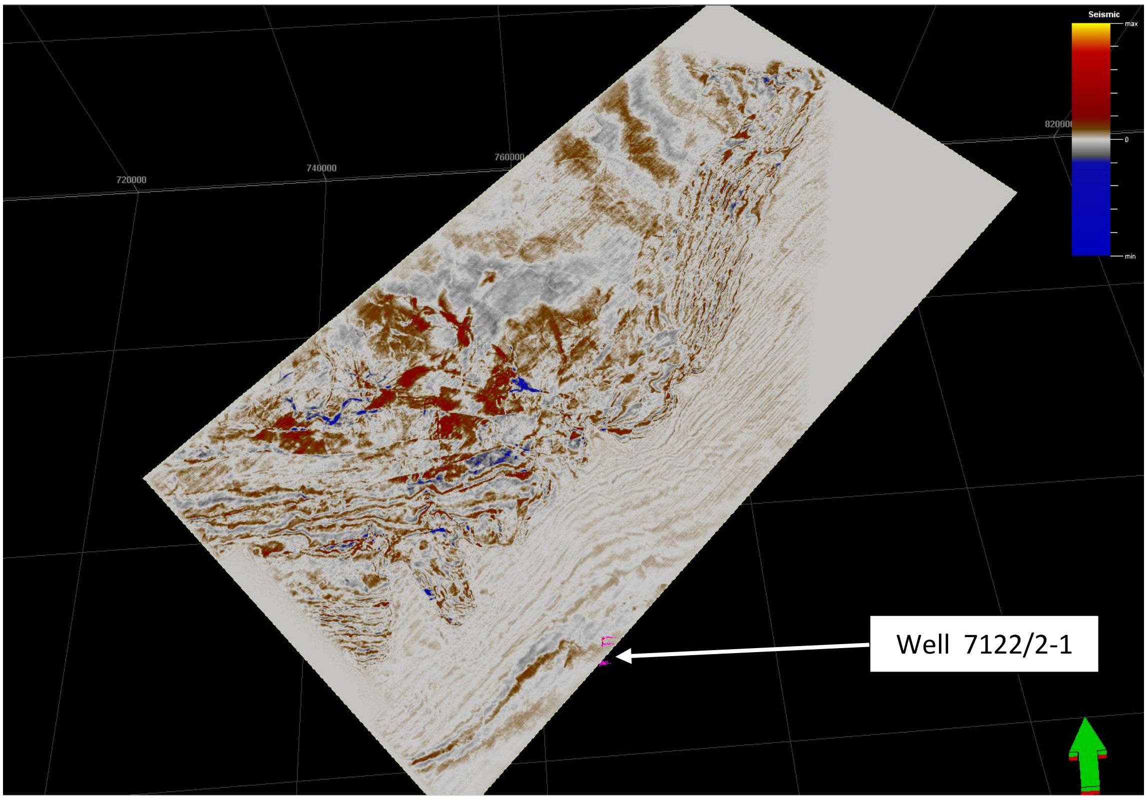


Figure 4.19. Time slice at 845 ms TWT showing the 3D coverage.

4.6.1. Data Quality

The well 7122/2-1 is located just on the southern edge of the 3D survey and will be used furthermore in the study for stratigraphic calibration and correlation.

The north eastern part of the survey is not of good quality and as illustrated in the Figure 4.19 above, the data have a limited extent within the 3D cube.

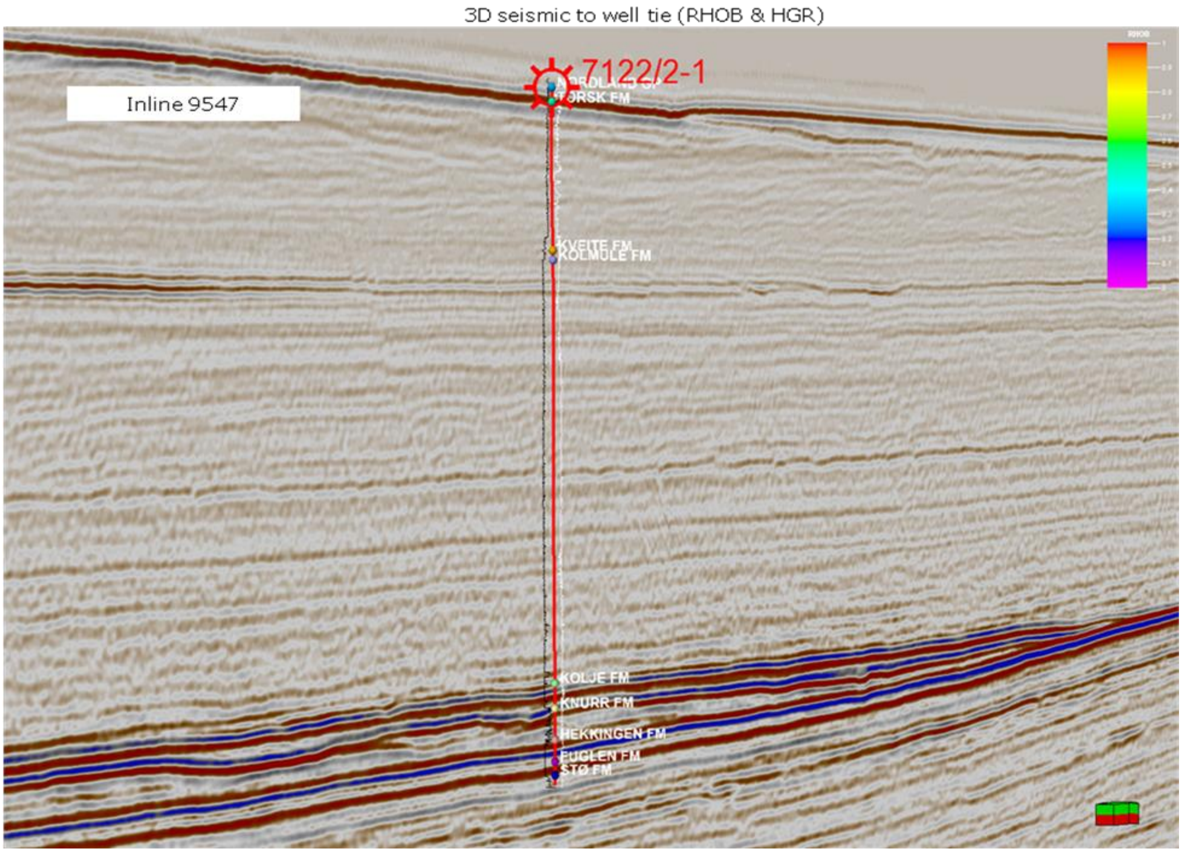


Figure 4.20. Inline 9547 tied with the well 7122/2-1.

The Inline 9547 in Figure 4.12 above shows the quality of the 3D lines. The color contrast is not so good; the major part of the line with low amplitude is very hard to distinguish. This problem could not be by changing the color code or by applying different contrasts.

This color problem was also observed on the 2D data from that area as showed on the next Figure 4.13. The cross line 6295 was compared with the 2D line AN88-4052. Both lines look similar but the problem could be fixed in the first case.

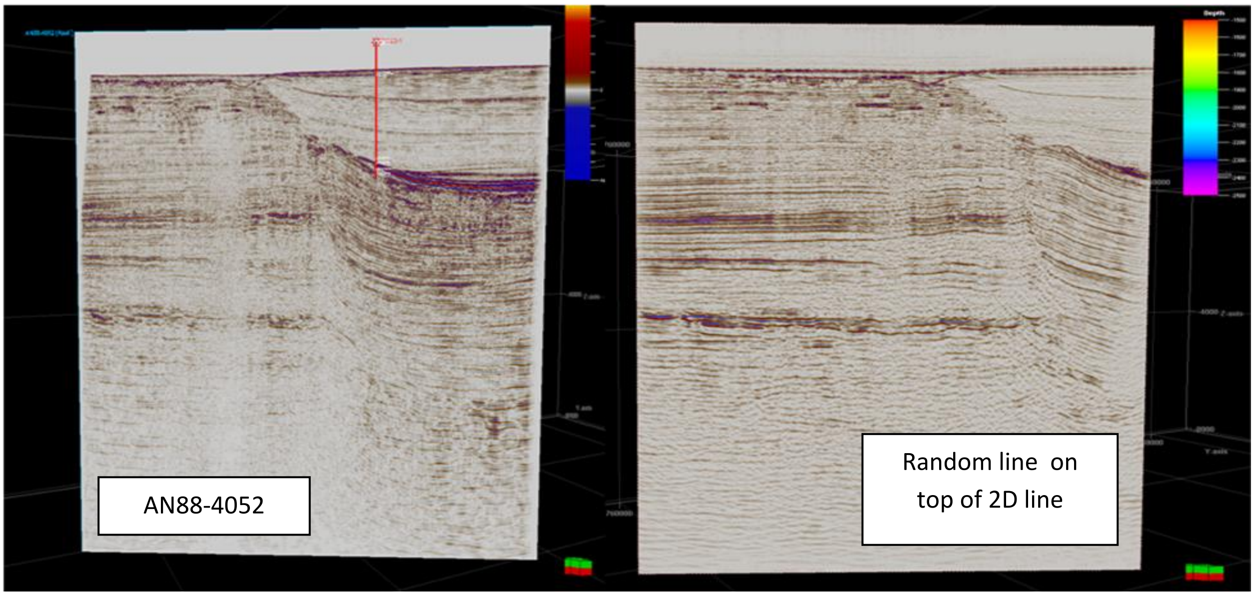


Figure 4.21. Comparison between the 2D line AN88-4052 and a random 3D line.

4.6.2. Interpretation of a random 3D line

This line was selected for interpretation because a special case can be observed.

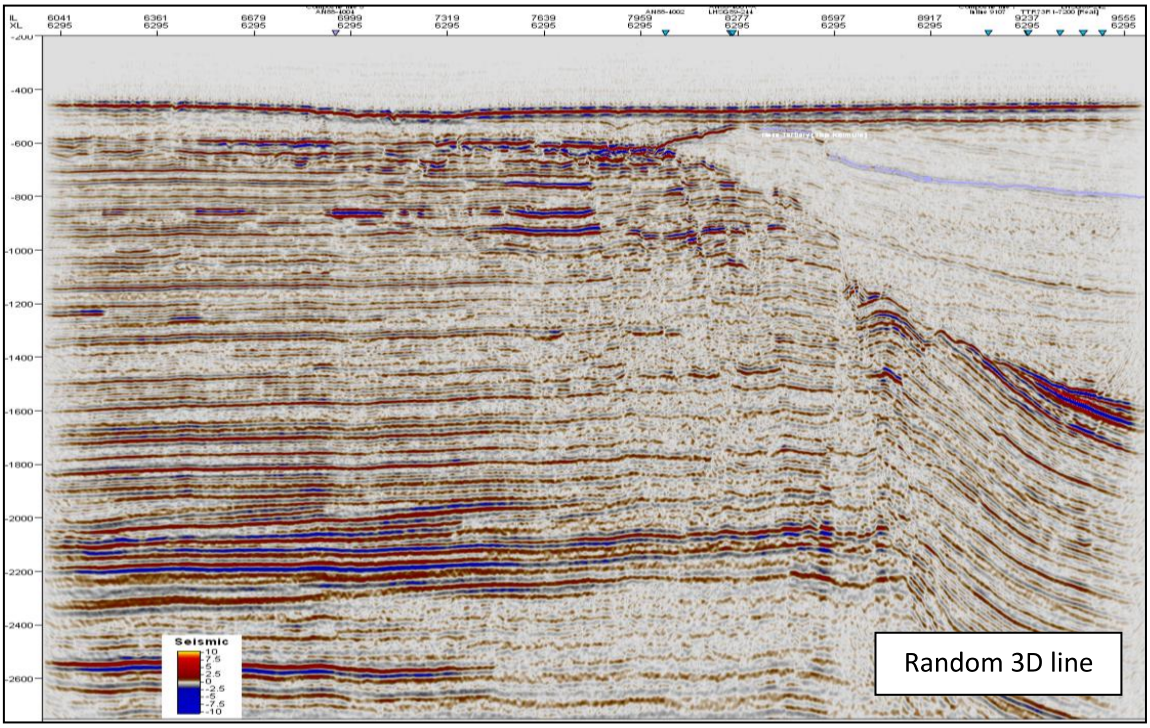


Figure 4.21. Interpretation of the Base Tertiary reflector on a random 3D line.

Interpretation of the Base Tertiary could be misleading because this reflector pinches out exactly at the point where the glacial sediments start to truncate the faulted marginal high (Figure 4.21.). But one can miss this point because of false continuity that these two different reflectors display on the picture.

This is the illustration of how high these glacial sediments could pass through the highest point in the Loppa High.

4.6.3. Time slice

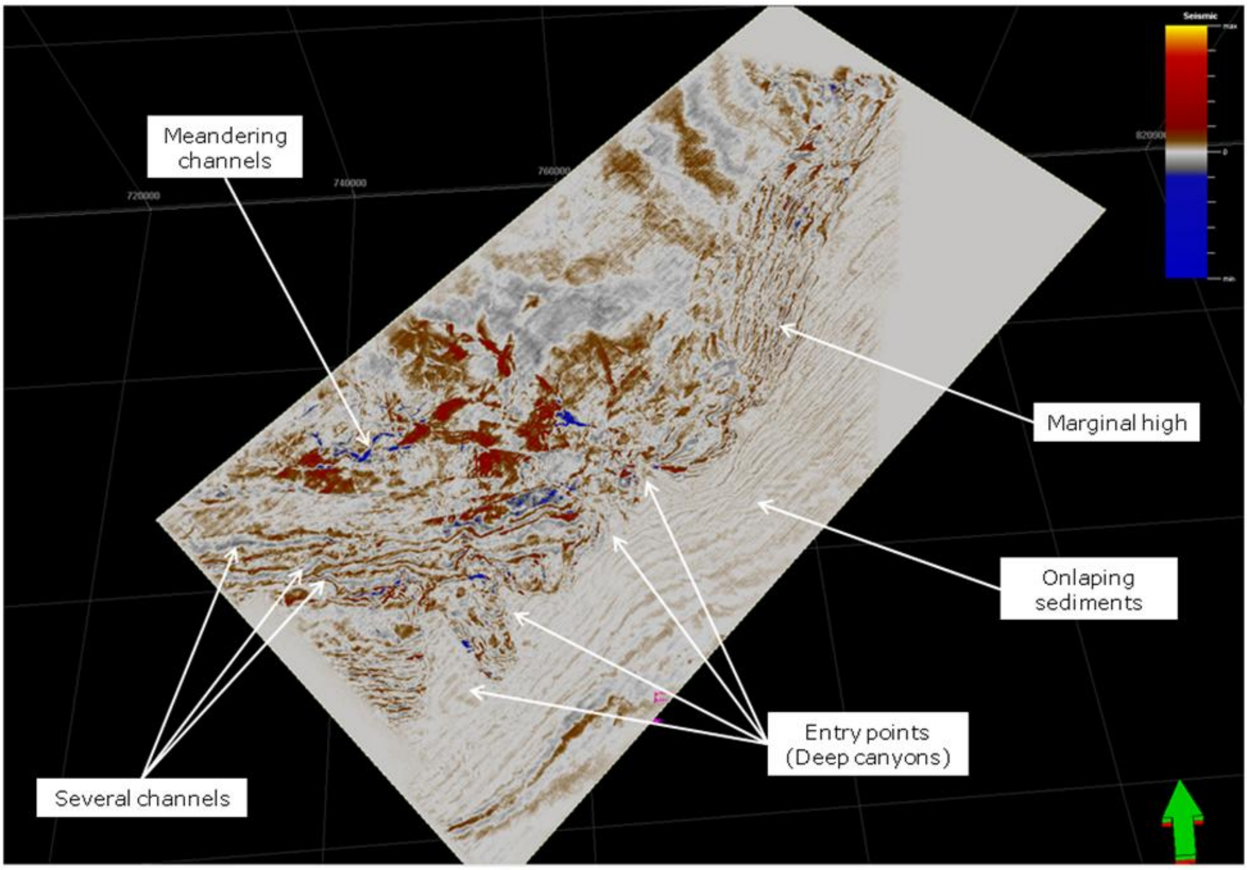


Figure 4.22. Time slice at 845 ms TWT.

4.6.4. Time structure map

Time structure map showing the surface of the Base Tertiary is shown in Figure 4.23.

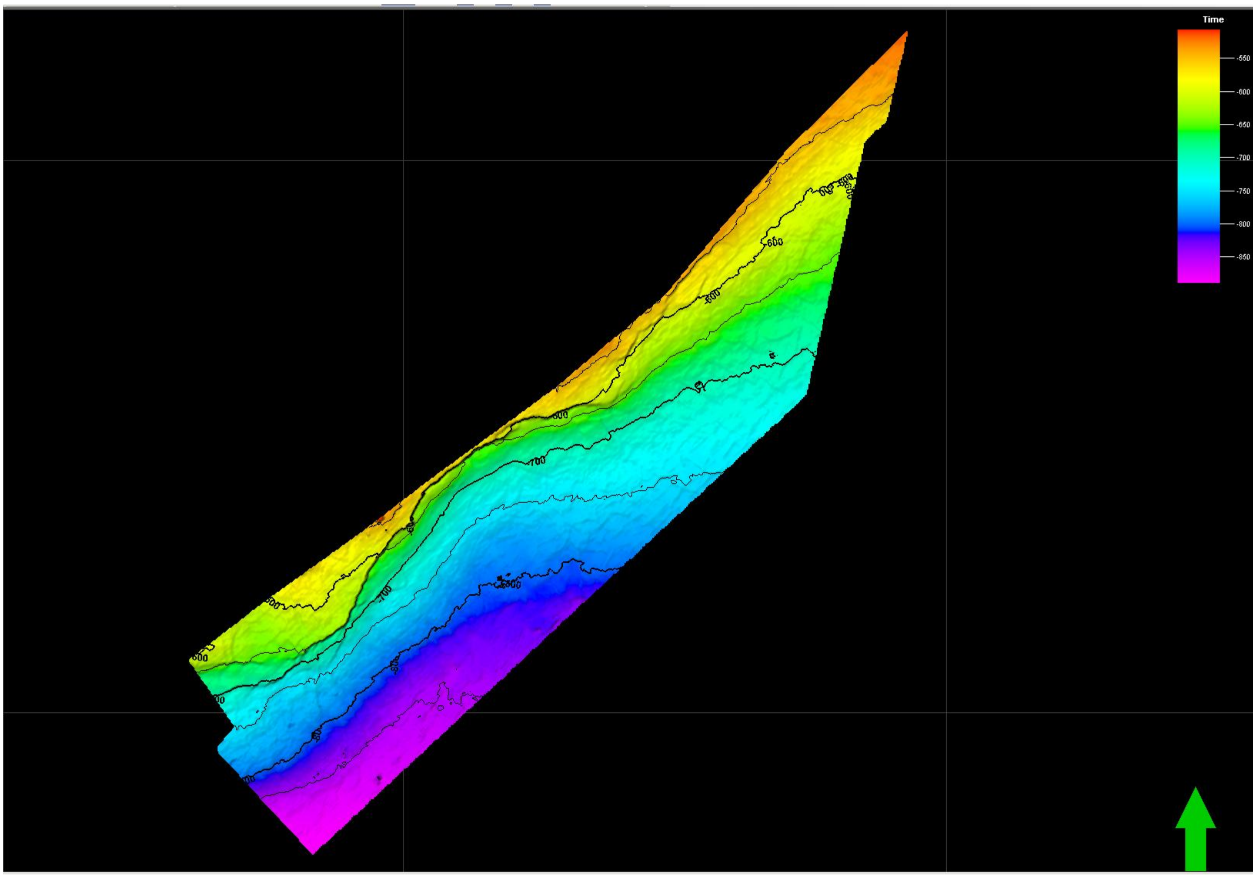


Figure 4.23. Base Tertiary time structure map.

5. Discussion

The results from the study are discussed in this section and a summary of the evolution of the Hammerfest Basin is given.

5.1. Evolution of the Hammerfest Basin.

The results of the seismic interpretation along the key lines and the chronostratigraphic charts showed that the evolution of the Hammerfest Basin from Late Triassic to recent can be divided into the following stages:

- Late Triassic – late Middle Jurassic (pre-rift)
- Late Middle Jurassic – earliest Cretaceous (syn-rift)
- Earliest Cretaceous – Early Cenozoic (post-rift)
- Late Cenozoic (regional uplift and erosion)

This division is reflected in the structure and the morphology of the different successions of sediments deposited within the basin.

5.1.1. Late Triassic - Late Middle Jurassic (pre-rift)

Late Triassic – Late Middle Jurassic times represent the period prior to the formation of the basin, when the Hammerfest Basin and the Loppa High were part of a vast cratonic province which occupied the Barents Sea region.

Sediments deposited during this period have generally parallel, high amplitude and laterally continuous reflections on the seismic sections, representing a succession of clastic beds such as shale and sandstone. The Snadd, Fruholmen, Tubåen, Nordmela and the Stø formations which compose the oldest seismic sequence in the study were deposited as a pre-rift sequence (Figure 5.1). These sediments were accumulated in a stable tectonic regime and a low energy context, both on the Loppa High and in the Hammerfest Basin. This is expressed by the low angle dip and the constant thickness of the layers and the lateral extent of the sequence over the study area and can be seen on the sections from the western part of the study area (see Figure 4.11).

Figure 5.1 summarize the geological evolution of the Hammerfest Basin, based on the results from this study which were correlated to a regional context, in the southwestern Barents Sea.

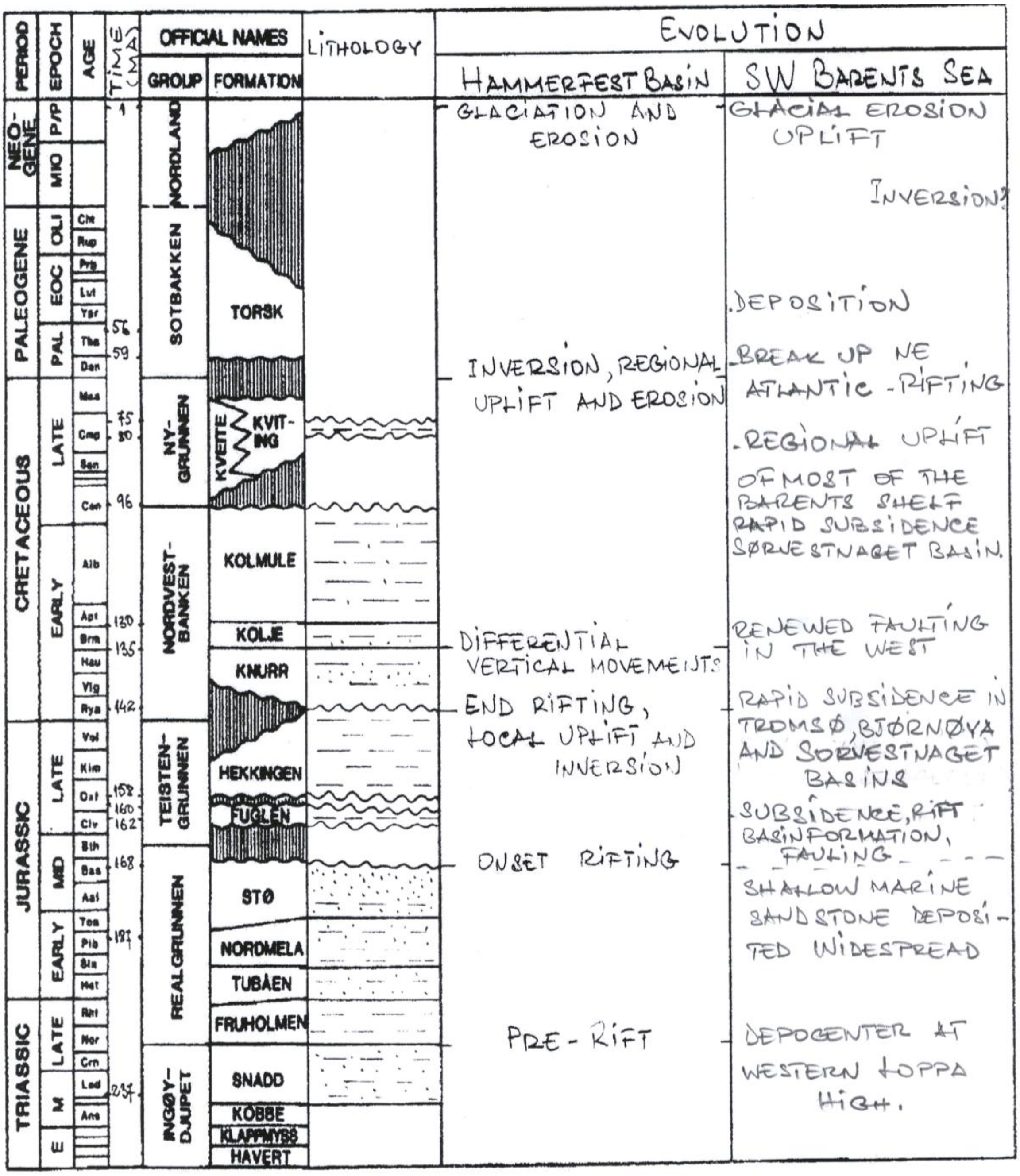


Figure 5.1. Summary of the geological evolution of the Hammerfest Basin.

5.1.2. Late Middle Jurassic – earliest Cretaceous (syn-rift)

The onset of rifting is marked by a hiatus in sediment deposition from the Bajocian to Callovian times (Figure 5.1).

This syn-rift stage in the study area is represented by a second seismic sequence which comprises two formations: the Fuglen and the Hekkingen Formations. The syn-rift sequence is easily recognized by the divergent pattern of the internal reflections which are faulted in the rotated fault blocks towards the crest of the central dome. Maximum subsidence occurred towards the main boundary fault. This is believed to have two origins: the main cause is the movement and the subsidence along the Asterias Fault Complex during the rifting, while at the same time, the central part of the Hammerfest Basin underwent doming in response to these tectonic activities on its border.

The main source rock interval within the Hammerfest Basin, the Hekkingen Formation was deposited during this period of subsidence.

This rift phase was a period of regional extension and minor strike-slip adjustments along old lineaments and the SW Barents Sea was rifted through the Hammerfest Basin during the Middle-Late Jurassic times (Faleide et al., 1993). An example of local inversion associated with the Asterias Fault Complex is showed in Figure 5.2.

During the pre-Late Jurassic time, the area was a part of a vast intra-cratonic platform with monoclinal strata dipping to the north, across the Asterias Fault Complex. In this figure, the end of Jurassic time shows a local uplift along the Asterias Fault Complex which start to develop. This is expressed by the positive flower structure which is developing. Such structures are the expression of compressional tectonic movements. The origin of which cause the movement might be initiated far from the basin (ocean break-up at the continental margin). As the faulted strata continue to raise, the flower structure which frames the area start to lose its stability and finally collapses. The uppermost strata in the crestal part are eroded. Products of erosion are accumulated in the basin and start to onlap on the flank of the rising Loppa High.

After collapsing, the flower structure regain stability as the sediment load from above has been removed, making the structure continue to be uplifted. And the process continues up until the recent time.

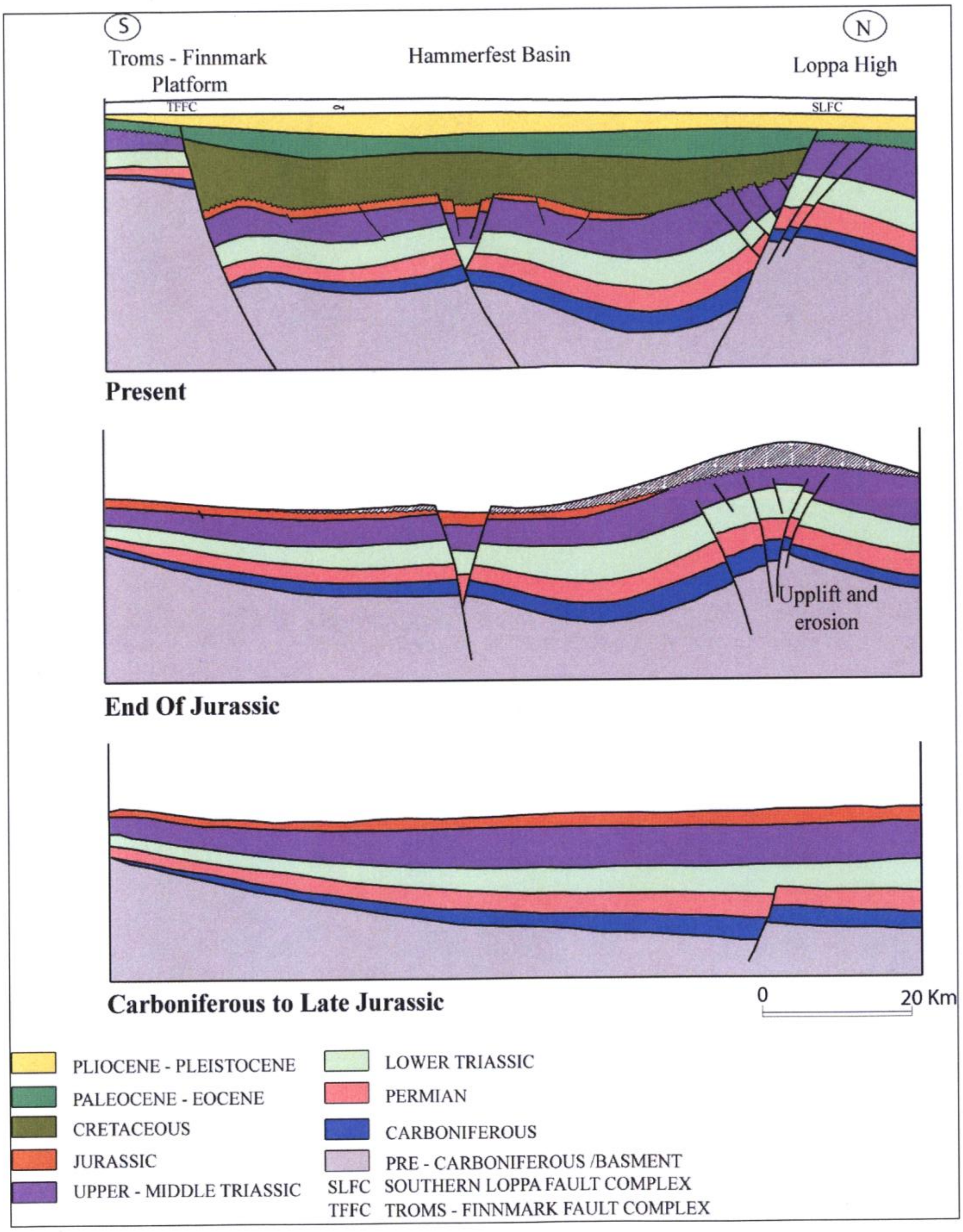


Figure 5.2. Example of local inversion in the evolution of the Hammerfest Basin.

5.1.3. Earliest Cretaceous – Early Cenozoic (Post-rift)

The onset of the post-rift stage is marked by a short hiatus separating sequence 2 and sequence 3 in Ryazanian times, "Base Cretaceous unconformity".

Post-rift sediments are represented by three seismic sequences deposited mainly during Early Cretaceous times, individually composed by the Knurr, Kolje and Kolmule formations.

The central dome formed in the Hammerfest Basin was totally covered by the end of Hauterivian time. This means that rifting events had ceased completely by this time.

Onlap of the post-rift sequences on the flank of the Loppa High mark the transgression of the Knurr, the Kolje and the Kolmule formations from the south to the north. This can be observed in the western part of the study area. In the central and eastern part of the Hammerfest Basin, they generally pinch out at the same location. An example can be seen in Figure 4.13 and on the map of the main faults and the erosional surface, together with the limits of the Lower Cretaceous sediments (Figure 4.1).

This can be explained by the rapid uplift of the Loppa High during the deposition of these successions. The uplift of the Loppa High continued throughout the post-rift phase, supplying the Hammerfest Basin with sediments.

The hiatus during Campanian-Danian times marks a new stage in the geological history of the study area. Regional uplift affected the Hammerfest Basin, the Loppa High area and most of the western Barents Sea except deep basins west of the study area. This regional uplift is believed to be linked to the opening of the Labrador Sea and regional subsidence centered along the North Atlantic rift basins (Faleide et al., 1993).

Late Cretaceous uplift and erosion is expressed by the absence of most of Upper Cretaceous sediments in the Hammerfest Basin. This movement affected most of the area of the Barents shelf, except in the Sørvestnaget Basin where a thick upper Cretaceous succession deposited during rapid subsidence.

During Paleogene times, deposition of sediments renewed. At the same time, minor reactivation of some faults took place. The reactivation is believed to be related to a breakup at the continental margin and expressed by the inversion associated with the Asterias Fault Complex during the post-Paleocene time which can be observed by the doming that affects all the strata from the Late Triassic to Paleocene (see Figures 4.7 and 4.9). Inversions are more restricted in a local scale and they take place during relatively short period of time, compared to regional uplift. Such events are recognized by the doming of affected strata.

5.1.4. Late Cenozoic (regional uplift and erosion)

Neogene is marked by a regional uplift and erosion mainly associated with Plio-Pleistocene glaciations. For the Hammerfest Basin/Loppa High area erosion estimates typically range between 1000 and 1500 m (Dimakis et al., 1998). During this period, the deposition of thick sediments in glacial fans is observed along the western margin (Faleide et al., 1996).

6. Conclusions

The geological history of the Hammerfest Basin can be divided into four main stages:

- Late Triassic – late Middle Jurassic (pre-rift)
- Late Middle Jurassic – earliest Cretaceous (syn-rift)
- Earliest Cretaceous – Early Cenozoic (post-rift)
- Late Cenozoic (regional uplift and erosion)

Late Triassic – late Middle Jurassic is a stable period during which a succession of clastic beds was deposited in a cratonic region including the Hammerfest Basin and the Loppa High. Widespread sand deposits were accumulated by the end of this pre-rift period.

In late Middle Jurassic – earliest Cretaceous times, a rift stage started with the subsidence caused by a regional extension creating the Hammerfest Basin. By the end of this period, an inversion took place raising the Loppa High with a positive flower structure while the central part of the Hammerfest basin underwent doming, in response to the tectonic movements at its boundary faults. The main source rock in the study area was deposited during this period.

In earliest Cretaceous – Early Cenozoic times, post-rift sediments were deposited in the Hammerfest Basin after short break, onlaping on the flank of raising Loppa High which acted as a sediment supplier. Regional uplift affected the Hammerfest Basin, the Loppa High and western Barents Sea province in Late Cretaceous, eroding the Upper Cretaceous sediments in the Hammerfest Basin. During Paleogene times, deposition of sediments renewed. At the same time, minor reactivation of some faults took place, expressed by the inversion associated with the Asterias Fault Complex.

And the last period Late Cenozoic is marked by a regional uplift and erosion mainly associated with Plio-Pleistocene glaciation.

References

Andrew, J., C., Di Primio, R., Scheck-Wenderoth, M., Horsfield, B., 2006, Severity and timing of Cenozoic exhumation in the southwestern Barents Sea, Journal of the Geological Society, London, Vol.163, p 761.

Barrère, C., Ebbing, J., Gernigon L., 2008, Offshore prolongation of Caledonian structures and basement characterisation in the western Barents Sea from geophysical modeling, Geological Survey of Norway, Tectonophysics 470 (2009), p 72, available at http://www.sciencedirect.com (accessed 20/06/2009).

Berglund, L., T., Augustson, J., Færseth, R., Gjelberg, J., and Ramberg-Moe, 1986, The evolution of the Hammerfest Basin, Habitat of Hydrocarbons on the Norwegian continental Shelf, Norwegian Petroleum Society (Graham & Trotman), p 319-338.

Dallmann, W., K., Gjeldberg, J.G., Harland, W.B., Johannessen, E.P., Keilen, H.B., Lønøy, A., Nilsson, I., Worsley, D., 1999, Committee on the Stratigraphy of Svalbard (SKS), Lithostratigraphic Lexicon of Svalbard, Review and recommendations for nomenclature use. Norwegian Polar Institute (Dallmann), p 184-209.

Dimakis, P., Braathen, B., I., Faleide, J., I., Elverhøi, A., Gudlaugsson, S., T., 1998, Cenozoic erosion and the preglacial uplift of the Svalbard-Barents Sea region, Tectonophysics, p 311-327.

Doré, A., G., Jensen, L., N., 1995, The impact of late Cenozoic uplift and erosion on hydrocarbon exploration: offshore Norway and some other uplifted basins, Global and planetary change, p 415-436.

Faleide, J., I., 2008, International Geological Congress Oslo, PETROBAR - petroleum related studies of the Barents Sea region. Available at http://www.cprm.gov.br/33IGC/1397251.html (accessed 25/11/2008).

Faleide, J., I., Erling, V., and Gudlaugsson, S., T., 1993, Late Mesozoic-Cenozoic evolution of the south-western Barents Sea in a regional rift-shear tectonic setting. Marine Petroleum Geology, vol 10, June.

Faleide, J., I., Gudlaugsson, S., T., Jacquart G., 1984, Evolution of the western Barents Sea, Marine Petroleum Geology, p 123-150.

Faleide, J., I., Solheim, A., Fiedler, A., Hjelstuen, B., O., Andersen, E., S., Vanneste, K., 1995, Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin, Global Planetary Change, p 53-54.

Faleide, J., I., Vågnes, E., and Gudlaugsson, S., T., 1993, Late Mesozoic evolution of the southwestern Barents Sea, The Geological Society, London, pp 933-950.

Gabrielsen, R., H., & Færseth, R., B., 1988, Cretaceous and Tertiary reactivation of master fault zones of the Barents Sea (extended abstract). *In:* W.K. Dallman, Y., Ohta & Andresen, A., (eds): Tertiary Tectonics of Svalbard. Extended abstracts from Symposium held in Oslo 26 and 27 April 1988. Norsk Polarinstitutt, Report Series, p 46, 93-97.

Gabrielsen, R., H., & Færseth, R., B., 1989, The inner shelf of North cape, Norway and its implication for the Barents Shelf-Finnmark Caledonide boundary. A comment. Norsk geologisk tidsskrift, p 69, 57-62.

Gabrielsen, R., H., 1984, Long-lived fault zones and their influence on the tectonic development of the south-western Barents Sea. Journal of Geological Society of London, p 141, 651-662.

Gabrielsen, R., H., Færseth, R., B., Jensen, L., N., and Kalheim, J., E., 1990, Structural elements of the Norwegian continental Shelf. NPD-Bulletin N°6, p. 12-15.

Gradstein, F., Ogg, J., Smith, A., 2004, A geologic Time Scale 2004, Cambridge University Press, p 342-343, 382 383.

Gudlaugsson, S., T., Faleide, J., I., Johansen, S., E., Breivik, A. J., 1998, Late Paleozoic structural development of the South-western Barents Sea, Marine and Petroleum Geology, p 85-86.

Hanisch, J., 1984a, West Spitzbergen Fold Belt and Cretaceous opening of the Northeast Atlantic. *In:* A.M. Spencer et al., (eds): Petroleum Geology of the North European continental Margin. Norwegian Petroleum Society. (Graham & Trotman), p 197-198.

Hanisch, J., 1984b, The Cretaceous opening of the Northeast Atlantic. Tectonophysics, p 101, 1-23.

Melberg, E., V., 2008, Gas discovery in the Barents Sea - 7222/11-1. NPD Press release 60/2008. Available at http://www.npd.no/English/Aktuelt/Pressemeldinger/2008/2008_10_31_pressem_60.htm (accessed 25/11/2008).

Nyland, B., Jensen, L., N., Skagen, J., Skarpnes, O., and Vorren, T., 1992, Teriary Uplift and Erosion in the Barents Sea: Magnitude, timing and Consequences, Elsevier, Amsterdam, Norwegian Petroleum Society, p 153-162.

Ramberg, I., B., Brihny, I., Nøttvedt A., Rangnes k., 2008, The making of land: Geology of Norway. Geological Society. Available at http://books.google.com/books?id=rMVNE0F2SckC&pg=PA390&lpg=PA390&dq=base+cretaceous+unconformity+in+the+Barents+Sea&source=bl&ots=pYgiMIpO7y&sig=flS_AQCU7d57RnoTKE0yvVxcTRw&hl=en&ei=71QcStmpLZaasgah9e2QAg&sa=X&oi=book_result&ct=result&resnum=1#PPA390,M1. p 380-390 (accessed 27/05/2009).

Riis, F., and Fjeldskaar, W., 1992, On the magnitude of the Late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents Sea, Elsevier, Amsterdam, Norwegian Petroleum Society, p 163.

Ritzmann, O., Faleide, J., I., 2007, Caledonian basement of the western Barents Sea, Tectonics, vol. 26, p 1-20.

Rønnevik, H., & Jacobsen, H., P., 1984, Structural highs and basins in the western Barents Sea. *In:* A.M. Spencer et al. (eds): Petroleum Geology of the North European margin. Norwegian Petroleum Society (Graham & Trotman), p 98-107.

Roufosse, M., C., 1987, the formation and evolution of sedimentary basins in the Western Barents sea. *In:*J., Brooks & K., Glennie (eds). Petroleum Geology of North West Europe. (Graham & Trotman), p 1149-1161.

Ryseth, A., Augustson, J., H., Charnock, M., Haugerud, O., Knutsen, S., M., Midbøe, P., S., Opsal, J., G., Sungsbø, G., 2003, Cenozoic stratigraphy and evolution of the Sørvestsnaget Basin southwestern Barents Sea, Norwegian Journal of Geology, p 107.

Worsley, D., 2006, The post-Caledonian geological development of Svalbard and the Barents Sea, NGF Abstracts and Proceedings, no. 3, p 7.

Ziegler, W., H., Doery, R., & Scott, J., 1986, Tectonic habitat of Norwegian Continental Margin. Norwegian petroleum Society (Graham & Trotman), p 339-354.